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# Feasibility of Performing a Suited 10-km Ambulation on the Moon
# Final Report of the EVA Walkback Test (EWT)


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# Executive Summary

The primary objective of this study was to collect human performance data and produce a crew consensus regarding the feasibility of performing a suited 10-km walkback. All subjects completed the 10-km walkback in less than 2 hours and completed the test with little difficulty working at about 50% of their aerobic exercise capacity.

A secondary objective of the study was to understand the specific human performance limitations of the suit compared to matched unsuited controls. Preliminary analysis indicated that the metabolic cost of the suit was significant ($> 3.5$ ml•min$^{-1}$•kg$^{-1}$) compared to unsuited controls. Weight-matched unsuited trials provided an initial estimate accounting for the metabolic cost of the suit due to the increased weight of the suit. But additional factors such as inertial mass, center of gravity (CG) alterations, pressure-volume work, and suit kinematic constraints could not be isolated. Additional tests will be needed to evaluate these other suit related factors.

Results of this test also clearly indicated that crewmembers in the MKIII suit may perform well on the Moon but may not perform well on Mars due to the increased gravity. In the lunar trials, the suited metabolic rates were all submaximal, whereas in the Mars-suited trials, subjects rapidly approached near maximal physiologic effort while brisk walking.

Proving human performance and suit biomechanical data for use in the suit and portable life support system (PLSS) design was another secondary objective. Baseline ambulation metabolic rates will allow for understanding of PLSS needs depending on the amount of ambulation expected in the lunar operational concepts. Oxygen transport cost values indicated that optimum efficiency was achieved at faster speeds for lunar-suited ambulation, but current cooling capabilities of the Shuttle extravehicular activity (EVA) suit and Apollo suits would be insufficient to take advantage of this improved efficiency.

Additional considerations from this test include the development and refinement of data analysis methods that will form a set of ‘standard measures’ for future studies that look at effects of suit weight, mass, pressure, CG, and kinematic constraints for both ambulation and exploration tasks. Tools resulting from the EVA Walkback Test include analysis software to rapidly post-process motion data to determine the number of cycles on any joint of the suit as a function of time and velocity, and to provide a quantitative index of stability. These analysis tools will be effective for developing suit cycle requirements and will provide significant cost savings during suit certification compared to the conventional methods of manual video tape review.

Finally, there were limitations to this study. Only 6 male astronauts participated in this study. The test team was unable to determine to what extent the POGO, unsuited harness and suited gimbal system affected performance from the limited data set. However, these data provide a critical step forward to understanding and quantifying suited human performance in reduced gravity. Future studies using different subjects, EVA suits, harnessing/gimbal systems, analog environments, and different tasks will be needed to foster a thorough understanding of how human performance is affected by EVA suits and reduced gravity environments.

# Introduction

As lunar exploration vehicle and EVA suit requirements mature, a critical question posed by the Constellation Program’s EVA Systems Project Office (formerly the Advanced EVA Office) is whether 1 or 2 surface rovers will be required to enable safe and efficient human exploration of the Moon (1/6 *g*) and Mars (3/8 *g*). The increased mass, volume, and cost associated with the launch and transport of 2 rovers to the lunar surface could be considerable and might not be necessary if it is possible for the crewmembers to walk back to a habitat in response to a failed rover. As a starting point, it was assumed that 10 km would be the maximum EVA excursion distance from a habitat based on anticipated lunar surface operational concepts and results from the Apollo program. A multi-disciplinary team was assembled from the Constellation Program's EVA Systems Project Office in collaboration with JSC's Space Life Sciences Directorate Human Research Facility's EVA Physiology, Systems & Performance (EPSP) Project to investigate the feasibility of performing a suited 10-km ambulation, (henceforth referred to as "walkback") independent of whether the subject walked, jogged, loped, or ran.

This study, the EVA Walkback Test (EWT) was designed not only to determine the feasibility of a 10-km walkback, but also to collect human performance data relevant to optimizing space suit design for the targeted operational environment. The basic approach involved performing suited tests with unsuited controls with the goal that specific physiologic and biomechanical parameters of the suit could be understood across a range of gravity levels and ambulation speeds. The series of tests comprising the EWT was conducted from January 31 through July 6, 2006.

### *Test Objectives*

The primary objective of this study was to collect human performance data and produce a crew consensus regarding the feasibility of performing a suited 10-km walkback.

The secondary objectives of the study were to:

1. Understand the specific human performance limitations of the suit compared to unsuited controls
2. Gain metabolic and ground-reaction force data to allow development of an EVA simulator to be used on future prebreathe protocol verification tests
3. Provide biomedical and human performance data for use in the suit and portable life support system (PLSS) design
4. Assess the cardiovascular and resistance exercise associated with partial-gravity EVA to be used in planning appropriate exploration exercise countermeasures.

These data also were envisioned to be used to develop more focused follow-on studies to understand interrelationships of such key parameters as suit mass, weight, pressure, and CG, and their respective influences on human performance.

## Methods

### *Subjects*

All subjects were recruited from a pool of personnel who typically perform EVA-suited studies for the Engineering Directorate and from the group of astronauts selected to support exploration EVA studies. Suit fit checks in the Mark III Advanced Space Suit Technology Demonstrator EVA Suit (MKIII) were performed on a range of subjects and only those who had good suit fit were selected for inclusion in this study, due to the projected length of the 10-km test and potential medical safety issues. Although still subjective in nature, some of the factors used by suit engineers to define good suit fit include elbow and knee break in the correct location, head position in the helmet opening, shoulders centered in the scye bearing opening, shoulder straps adjusted correctly, heel-to-crotch and crotch-to-shoulder length correct, and overall arm and leg length correct. Ideally, the suit should fit with as little gap between the suit and subject as possible while still allowing the subject to be comfortable and to move as well as possible within the joint mobility capabilities of the suit. From this list, 6 male astronaut subjects (Table 1) participated in the data collection phases of the study, including the 10-km portion (2 backup subjects including 1 female performed only the $VO_2pk$ test.) At the time of the test, no available female astronauts properly fit in the MKIII suit.

**Table 1. Summary of EWT Subject Characteristics**

| | Minimum | Mean ± SD | Maximum |
|---|---|---|---|
| Age (yrs) | 40 | 46.8 ± 4.3 | 51 |
| Body mass (kg)<br>*(lbs)* | 71.2<br>*157.0* | 81.4 ± 7.8<br>*179.5 ± 17.2* | 89.4<br>*197.0* |
| Height (cm)<br>*(inches)* | 175.3<br>*69.0* | 180.3 ± 5.0<br>*71.1 ± 2.0* | 188.0<br>*74.0* |
| $VO_2pk$ ($ml \cdot kg^{-1} \cdot min^{-1}$) | 40.8 | 48.7 ± 5.7 | 55.6 |

All subjects successfully passed a modified Air Force Class III Physical or equivalent examination. Each subject was provided verbal and written explanations of the testing protocols and the potential risks and hazards involved in the testing, and signed NASA JSC Human Research documentation indicating their understanding and consent. All testing protocols were reviewed and approved by NASA JSC Committee for the Protection of Human Subjects and appropriate test readiness reviews (TRR) were conducted prior to testing.

## *Test Hardware*

### Partial Gravity Simulator (POGO)

All EWT data collection sessions were performed using the Space Vehicle Mock-up Facility (SVMF) POGO system to provide simulated partial-gravity conditions. The POGO uses a pneumatic cylinder servo-controlled to a strain gauge to result in a constant gravitational offloading throughout the subject's vertical range of motion. The servo system consists of the vertical servo assembly, strain gauge, pneumatic cylinder assembly, and the piston rod assembly (ref. drawing JSC-26802-4). The POGO rides along a linear air bearing rail further allowing constant gravitational offloading in one horizontal plane (either fore/aft or left/right depending on orientation of the subject. A gimbal support structure attached to the end of the lifting actuator supports a suited subject and allows for the pitch, roll, and yaw rotational degrees-of-freedom during movement.

Simulations of 1/6 *g* and 3/8 *g* were accomplished using an overhead gimbal with a suit attachment system consisting of a "spider/stinger" combination allowing for adjustment of the fore/aft (stinger) and up/down (spider) positioning of the suited subject in relation to the gimbal axes of rotation. The spider attached to the PLSS mock-up of the MKIII suit, thereby allowing the POGO to partially lift the subject as shown in Figure 1, thus simulating a reduced gravity condition. Spider and stinger settings were adjusted until the subject and test evaluators subjectively determined that the total system CG positioning allowed the subject to move and ambulate as freely as possible without pushing the subject forward or pulling the subject backward. During unsuited testing, a spreader bar and harness assembly provided support to the suspended subjects (see Figure 3). Further details of the POGO system and subassemblies can be found in the SVMF Work Instructions (SVMF-OPS-W0012, Rev. I).

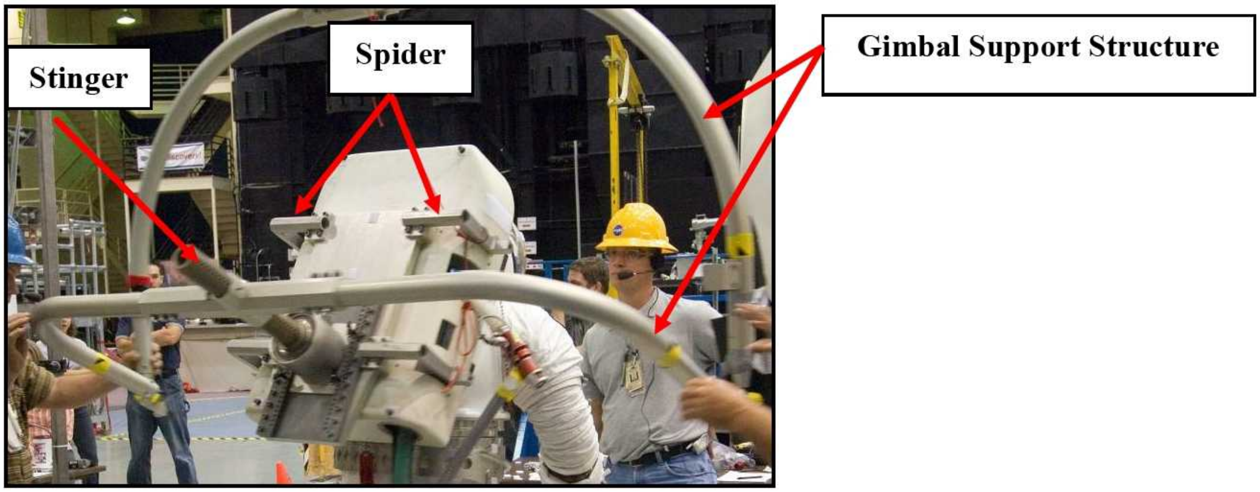



**Figure 1. Gimbal support structure with spider and stinger attachment to MKIII suit**

For the unsuited trials, the POGO system was adjusted to completely offload the weight of the harness and spreader bar, while the subject's weight was offloaded to simulate the appropriate gravitational level. For suited trials, the combined weight of the subject, liquid cooling garment (LCG), pressure garment (MKIII), portable life support system (PLSS) mockup, and gimbal support structure were offloaded to the appropriate gravity level. The combined 59 kg weight of the PLSS backpack mock-up (18 kg) and the gimbal support system (41 kg) closely simulates the 61 kg PLSS weight of the Crew and Thermal Systems Division's (CTSD) baseline design at the time the test was conducted. These configurations were designed to create realistic configurations for the respective unsuited and suited conditions.

### Mark III Advanced Space Suit Technology Demonstrator EVA suit

For suited testing, the MKIII (also known as the H-Suit) suit was used because it represents a suit concept that provides dynamic ranges of motion considered necessary for a wide variety of planetary EVA tasks within today's technology level, given other constraints that must be considered in pressure garment design (Figure 2). Thus, the MKIII provides a valid test bed from which attainable requirements for future suit development can be derived. The MKIII is a hybrid space suit configuration composed of hard elements, such as a hard upper torso and brief section, and of soft components such as fabric elbows and knees that are designed to handle operating pressures of up to 55 kPa (8.0 psi). Another desired feature of the suit for testing purposes is the use of bearings in multi-axial mobility joint systems featured in the shoulder, upper arm, waist, upper hip, mid hip, upper leg (3 bearing hip), and ankle joints. The suit is entered through a hatch on the backside of the hard upper torso (rear entry suit) that also accommodates integration of a backpack. Suited subjects are integrated to the suit by shoulder straps. The boots are modified commercial work boots with flexible soles for walking and a convoluted ankle joint for mobility.

The MKIII has modular leg, arm, and boot soft goods components that allow individualized sizing adjustments with metal sizing rings. Foam padding also is used to improve fit and to avoid discomfort or injury due to suit contact with the subject creating pressure points or repeated rubbing.

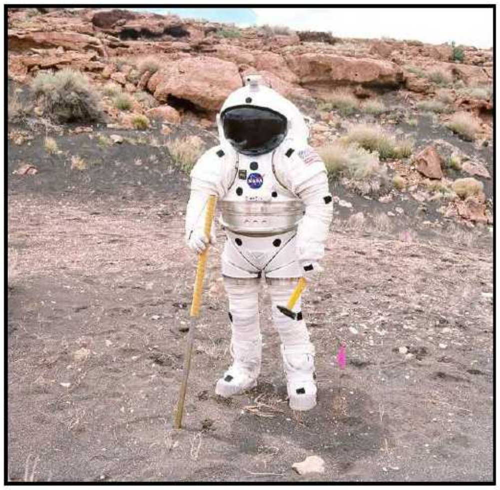


**Figure 2. MKIII Advanced Space Suit Technology Demonstrator EVA Suit**

During testing sessions certified breathing air was provided by a compressed air source at a standard flow rate of 170 L/min (6.0 cubic feet per minute) through a manifold and transfer hoses and reduced to 29.6 kPa (4.3 psig). An ice/water mixture to cool the test subject was delivered by an external pump (~55 kg/hr) from a suit chiller to the LCG worn under the suit. Communication with the suited test subject was available via a system comprised of 9 wireless headsets and 2 hardwire headsets. The hardwire headsets were assigned to the subject and the medical monitor, and could be isolated from the wireless headsets in the event a private medical conference was required. Subsequent references in this report to the "suit" include the pressure garment and combined mockup backpack and gimbal support structure.

### Challenger Treadmill

The treadmill used was a commercial off-the-shelf Challenger model 5.0 owned by the EVA & Spacesuit Systems Branch. With a walking surface 27 inches wide and 72 inches in length, it allows speeds from 0.05 to 4.5 $m \cdot s^{-1}$ (0.1 to 10.0 mph) with speed resolutions of 0.045 $m \cdot s^{-1}$ (0.1 mph). The treadmill was equipped with 4-AMTI force plates provided by the Anthropometry and Biomechanics Facility (ABF) as described under Data Collection Techniques.

## *Testing Protocols*

### Partial Gravity System Characterization

To evaluate the POGO system's ability to provide the necessary simulated gravitational offloading through a subject's range of motion, time series motion analysis equipment, and ground-reaction force (GRF) plates were used to provide an independent assessment of the POGO system performance. Two subjects performed submaximal treadmill ambulation on a level treadmill (0% grade) at 1/6 *g* and 3/8 *g* in shirt-sleeve conditions using the POGO system. The total body center of mass (COM) trajectory approximated using the 3-dimensional motion analysis data of marker placed on the trochanter for 3 different speeds for each subject in each gravity level. The measured downward acceleration was then derived from the maximum displacement of the COM until the point of foot-strike with the treadmill. **Table** 2 depicts the measured versus theoretical downward acceleration and the percentage error for each subject. The percentage error between the theoretical and measured accelerations showed some variation with speed and gravity level, but averaged within 5% for both subjects. This suggests that the POGO was performing within acceptable limits and was determined to be appropriate for use in this study. This phase of the EWT was performed from January 31 to February 3, 2006.

**Table 2. Measured versus theoretical downward accelerations**

| Subject | Speed ($m•s^{-1}$) | Gravity Level | Actual Acceleration ($m•s^{-2}$) | Theoretical Acceleration ($m•s^{-2}$) | % Error |
|---|---|---|---|---|---|
| 1 | 1.68 | Lunar | 1.76 | 1.63 | 7 |
| 1 | 2.12 | Lunar | 1.84 | 1.63 | 13 |
| 1 | 2.57 | Lunar | 1.67 | 1.63 | 2 |
| 2 | 1.57 | Lunar | 1.55 | 1.63 | 5 |
| 2 | 2.01 | Lunar | 1.59 | 1.63 | 3 |
| 2 | 2.45 | Lunar | 1.48 | 1.63 | 10 |
| 1 | 1.99 | Mars | 3.65 | 3.68 | 1 |
| 1 | 2.43 | Mars | 3.59 | 3.68 | 2 |
| 1 | 2.88 | Mars | 3.58 | 3.68 | 3 |
| 2 | 2.12 | Mars | 3.58 | 3.68 | 3 |
| 2 | 2.58 | Mars | 3.43 | 3.68 | 7 |
| 2 | 3.01 | Mars | 3.75 | 3.68 | 2 |

### $VO_2$ Peak Test

To compare energy expenditure across the different conditions planned for this test, subjects performed a graded treadmill exercise test to determine their aerobic capacity via measurement of peak oxygen consumption, or $VO_2$pk. The test began with a 5-minute warm-up at 1.56 $m•s^{-1}$ followed by 3 stages lasting 3 minutes each on a level surface, starting at 2.68 $m•s^{-1}$ and increasing 0.45 $m•s^{-1}$ at the start of each new stage. After the third stage, the speed remained the same and the incline on the treadmill surface was increased 3% at the start of each subsequent minute (Lee, et al., 1997; Watenpaugh, et al., 2000). The subject continued exercising through these stages as long as possible, to maximal effort. $VO_2$pk and peak heart rate were determined by the highest 1-minute average attained during the test. From the $VO_2$pk, measured levels of energy expenditure during subsequent test sessions can be evaluated as percentages of $VO_2$pk to ensure subject safety and allow valid relative comparisons among subjects. This phase of the test was performed in the Exercise Physiology Laboratory from March 9 to April 18, 2006.

### Determination of Actual and Theoretical Preferred Transition Speed

Originally, the plan was to determine subject speeds by use of Froude numbers, which provide a potentially unifying theory for the combined effects of speed, size, and gravity on locomotion biomechanics (Donelan & Kram, 1997) under the assumption of the inverted pendulum model (Cavagna et al., 1977). This method can conceivably allow some to compare a walk or run in 1 *g* to the same walk or run in another gravity even though they might be at different speeds. The Froude equation is: $Fr = v^2/gL_{leg}$, where v = locomotion velocity, *g* = acceleration due to gravity, $L_{leg}$ = leg length. Under 1-*g* conditions, research has shown that humans change from a walk to a run at a Froude number of approximately 0.5 (Hreljac, 1995). This trend of moving from a walk to run at 0.5 has been proposed to be consistent independent of gravity level based on the theory of dynamic similarity (Donelan & Kram, 1997). Therefore, the predicted preferred-transition speed (PTS) for each subject was computed as the speed corresponding to Fr = 0.5 with $g = 1.63$ $m \cdot s^{-2}$ (lunar gravity) or $g = 3.68$ $m \cdot s^{-2}$ (Mars gravity). Assigned speeds would then be at Froudes of 0.35, 0.4, 0.45, 0.55, 0.6, and 0.65 to test walking and running speeds and stay out of the transition speed zone. Before proceeding with this method to determine test speeds, the actual PTS from walking to running had to be measured for each subject and compared to the theoretical results based on the Froude number.

To establish accurate baseline metabolic and biomechanical data for a range of walking and running speeds, it was first necessary to determine the PTS. Therefore, prior to their unsuited energy velocity test, each subject's PTS was determined at 1/6 *g* and 3/8 *g*. The subject, wearing normal exercise clothes and modified parachuting waist/hip harness, was connected to the POGO and offloaded to the desired gravity level. The treadmill speed was set so the subject was clearly walking (where at least one foot was in contact with the ground at all times). Once a steady gait was achieved, the treadmill speed was increased by 0.05 to 0.09 $m \cdot s^{-1}$. The speed was then held constant until steady gait was achieved, and the preceding steps repeated until a speed was reached at which the subject freely chose to run. Subsequently the treadmill speed was adjusted to find the exact speed where 1) the subject remained walking, but had to exert increased effort to do so, 2) the subject exerted significant effort to avoid drifting rearward on the treadmill, and 3) the subject indicated that they would prefer to slowly jog at that speed if required to do so for an extended length of time. The speed at which all 3 criteria were met was noted as the PTS. Time permitting, subjects then walked at 0.09 $m \cdot s^{-1}$ above and ran at 0.09 $m \cdot s^{-1}$ below the transition speed and metabolic data were collected to confirm the accuracy of the transition speed. Once the unsuited PTS was determined for each gravity level, 3 walking and 3 running velocities were assigned (Table 3) such that the PTS and immediate range above and below it would be avoided during data collection as there is usually a range of speeds around the PTS that are neither comfortable to walk nor run in. Three speeds were selected for data collection to allow investigators to understand the shape of the metabolic curve in both the walking and running ranges.

**Table 3. Determination of speeds used for the Energy-Velocity tests at 1/6 g and 3/8 g**

| **Speeds Used for the Energy-Velocity Tests:** | | |
|---|---|---|
| **Stage** | **Speed** | **Comments** |
| 1 | PTS minus 0.49 $m \cdot s^{-1}$ (1.1 mph) | Need smaller incremental steps for walking because bottom end of range is reduced |
| 2 | PTS minus 0.36 $m \cdot s^{-1}$ (0.8 mph) | |
| 3 | PTS minus 0.22 $m \cdot s^{-1}$ (0.5 mph) | Assures walking out of transition zone |
| **PTS Zone** | | **No data collected in PTS zone** |
| 4 | PTS plus 0.22 $m \cdot s^{-1}$ (0.5 mph) | Assures running out of transition zone |
| 5 | PTS plus 0.67 $m \cdot s^{-1}$ (1.5 mph) | Larger incremental steps distinguish differences at running speeds |
| 6 | PTS plus 1.12 $m \cdot s^{-1}$ (2.5 mph) | |

### Unsuited Energy-Velocity Tests

During the unsuited energy velocity tests, each subject performed submaximal locomotion on a level treadmill (0% grade) for 3 minutes at each of the 6 different velocities based on the PTS determination (Table 3). Speed selection at 1 *g* was determined by the Froude number with speeds at Froudes of 0.35, 0.4, 0.45, 0.55, 0.6, and 0.65. Simulations of 1/6 *g* and 3/8 *g* were accomplished by having subjects wear a modified parachuting waist/hip harness that allowed the POGO to partially lift a weight equivalent to the desired gravity level as shown in Figure 3.

**Figure 3. Instrumented subject performs unsuited energy-velocity test while partially suspended from POGO**

Subjects completed a total of 5 trials during this session, 3 trials using true 'unsuited' weight relief and 2 in which the subject's weight was offloaded to match what the subject would weigh if wearing the MKIII suit at the respective gravity level. This approach was used to provide weight-matched controls, which could account for the specific increase in metabolic rate due to the increase in weight while wearing a suit. Also, when compared to later suited tests, this would allow assessment of the specific metabolic costs of the suit (i.e., the combined effects of inertial mass, pressure-volume work, and kinematic constraints). The trials are described following and in Figure 4.

"Unsuited" condition
Trial 1: Earth gravity (1 *g*), wearing harness
Trial 2: Moon gravity (1/6 *g*), wearing harness
Trial 3: Mars gravity (3/8 *g*), wearing harness

"Weight-matched" condition
Trial 4: Moon gravity (1/6 *g*), wearing harness <u>with</u> simulated weight
Trial 5: Mars gravity (3/8 *g*), wearing harness <u>with</u> simulated weight

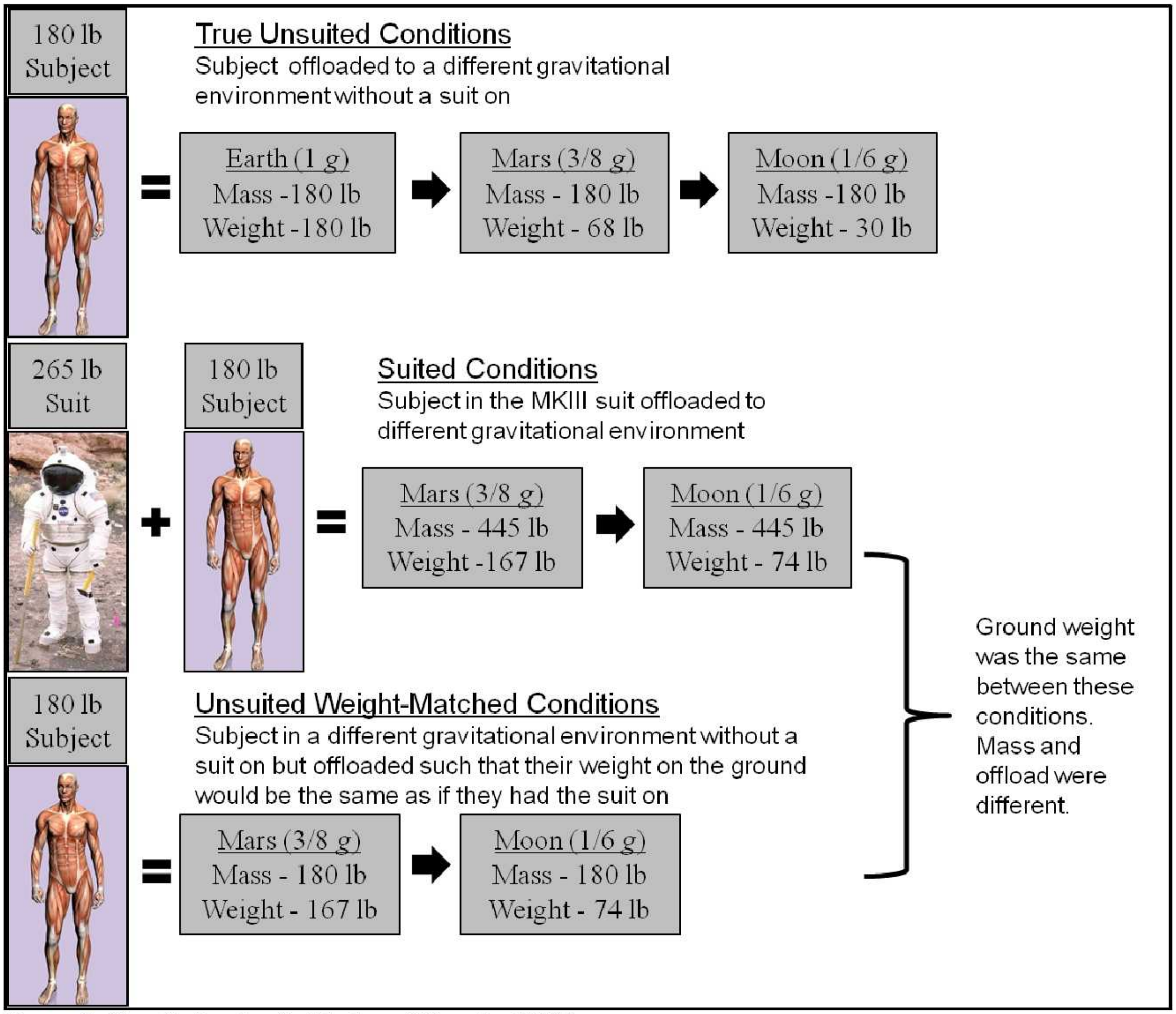



**Figure 4. Unsuited and suited test conditions for EWT**

Each subject initially performed Trial 1 and then the order of subsequent trials was varied systematically such that half the subjects completed the 1/6-*g* condition (Trial 2) next and half completed the 3/8-*g* condition (Trial 3) next to address test order and learning bias. This phase of the EWT was performed in the SVMF from April 27 to May 10, 2006, with makeup sessions on July 5–6, 2006.

**Suited Energy-Velocity Tests**

Each subject performed suited submaximal treadmill translation on a level treadmill (0% grade) at 1/6 *g* and 3/8 *g* (seeFigure 5). A trial at 1 *g* was not performed because of the potential for suit damage and expected near maximal levels of subject exertion needed. Translation speeds (3 walking, 3 running) and durations (3 minutes/stage) for each individual were set to be identical to those used during the unsuited tests for walking. While this was the case for 4 subjects, 2 subjects had running velocity increments set at half those of the unsuited trials (0.22 $m \cdot s^{-1}$ versus 0.45 $m \cdot s^{-1}$ or 0.5 mph versus 1.0 mph, respectively) due to the difficulty of moving the MKIII suit at higher speeds. This still ensured that 2 of the 3 running speeds would be identical to their unsuited trials for comparison between conditions. For example, one subject's running speeds unsuited were 1.67, 2.12, and 2.57 $m \cdot s^{-1}$ and suited speeds were 1.67, 1.90, and 2.12 $m \cdot s^{-1}$ ensuring that the 1.67 and 2.12 $m \cdot s^{-1}$ speeds would be matched. Gravity level trials were balanced in the same manner as during the unsuited tests. At the end of the 1/6-*g* trial, each subject was asked to identify the velocity at which they expected they would want to perform the 10 km-walkback session. This phase of the EWT was performed from May 19 to May 26, 2006.


**Figure 5. Suited subject performs treadmill locomotion while partially suspended from POGO**

### Suited 10-km Walkback Test

For the 10-km walkback test sessions, in addition to the set-up for the suited energy velocity tests, subjects were outfitted with a wireless ECG system that delivered a 3-lead ECG signal to the medical monitor console. Subjects were also provided a low-profile 32 oz in-suit drink bag from which water could be consumed as needed during the test. This bag was affixed with Velcro to the sternum area of the inner suit torso, with a bite valve placed near the crewmember's mouth. This configuration was a special accommodation for this test because of the expected duration of the exercise. Subjects were encouraged to stop the walkback at any time to access the drink bag or for any other reason if they felt it was necessary.

Subjects were informed before the test session that the velocity would be self-selectable and changeable at any time they desired. They were also made aware that suit cooling could limit the velocity at which they could run. The testing scenario described the subject to be 10 km from a lunar habitat, having completed approximately 4 hours of surface activities during which their rover breaks down and is unable to transport them back to the habitat. The subjects were reminded of the test termination criteria (Appendix A) and ground rules (Appendix B) and given the following basic instructions:

1. Attempt to translate 10 km at any speed you desire. Speed can be increased or decreased whenever you request; there is no time requirement. You may stop and rest at any time you wish. You may also request the test be stopped at any time, for any reason.
2. You will be prompted every 15 minutes for ratings of exertion, compensation, and discomfort. If at any time you experience discomfort, please tell the test team, regardless whether it occurs at the designated interval.
3. Because of the potential for injury, do not press through excessive levels of discomfort. Should you need to stop the test before reaching 10 km, calculations based upon the completed portion of the test can allow the team to extrapolate nominal expected time to completion and other associated data.

This phase of the EWT was performed in the SVMF from June 5 through June 26, 2006.

## *Data Collection Techniques*

### Metabolic Data Collection

During the $VO_2$pk and unsuited tests, energy expenditure (i.e., metabolic rate) was determined from the continuous measurement of $VO_2$ and carbon dioxide ($CO_2$) production ($VCO_2$) using a headset/mouthpiece connected to a True One 2400 metabolic cart (Parvo Medics, Provo, UT). Heart rate (HR) during the $VO_2$pk test was monitored from 12-lead electrocardiogram (ECG) recordings. During submaximal tests, HR was monitored via a Polar Heart Rate Monitor.

During exercise in the MKIII suit, energy expenditure was based on measured suit ventilation rate, expired $CO_2$ concentration in the exhaust umbilical (via a CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, PA), and the regression between $VCO_2$ and $VO_2$ as measured during the $VO_2$ peak test. This technique and hardware were identical to those currently used by the Environmental Physiology Laboratory during suited tests at the Neutral Buoyancy Lab. The suit ventilation loop begins at the top back end of the helmet and airflow is directed over the top of the head and down the face to wash out expired air and exhausts through a port located near the subject's lower back. The ventilation rate and direction of airflow ensures proper gas mixing throughout the suit and exhaust umbilical and that there are no pockets of expired air that collect in the helmet or elsewhere. The suit has a known leak rate; therefore, ventilation was measured on the inlet side only. Also, given the suit's airflow and mixing characteristics and steady state exercise protocols, we are assured that gas sampled at the exhaust umbilical is representative of the subject and not affected by the known leak rate.

Thermoregulatory demand was determined only during the 10-km sessions from measures of body core and skin surface temperatures. Core temperature was determined using a radio frequency capsule while skin temperatures were measured using thermocouple sensors, both transmitted to a wireless VitalSense® physiological monitor (Mini Mitter Company, Inc., Bend, OR). Standardized equations were used to calculate body heat storage (Kuznetz, 1976).

In comparing the metabolic costs of different suited conditions, it is important to define some level of metabolic rate that is deemed significant. Due to the limited sample size ($n$=6), inferential statistics were not used; therefore, statistical significance was not calculated. For these analyses a metabolic rate of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ was chosen for practical significance. This is equivalent to resting metabolic rate and 10% of the $VO_2$pk in a subject with a $VO_2$pk 35 $mL \cdot kg^{-1} \cdot min^{-1}$ who would be representative of a slightly deconditioned crewmember. The average ISS crewmember has a preflight $VO_2$pk of $43.7 \pm 6.1$ $mL \cdot kg^{-1} \cdot min^{-1}$ (NASA Exercise

Physiology Lab Database). For the energy-velocity series of testing, metabolic rates represent the highest 1-minute average during each of the 3-minute walking or running stages. The best second order polynomial fit is shown as the trend line.

**Biomechanical Data Collection**

Biomechanical data were collected using a 12-camera motion analysis system (120 Hz; Vicon, Oxford, UK) and 4 strain-gauge force plates (AMTI, Watertown, MA). The force data were then processed and analyzed using customized MATLAB computer programs. Data were sampled during 20 full, consistent strides during each stage of testing; however, during the 10-km sessions, data were sampled for 20 strides every 5 minutes. Ground reaction forces were collected using 46.2 × 50.8 cm force plates, mounted to each corner support structure of the treadmill (Figure 6).

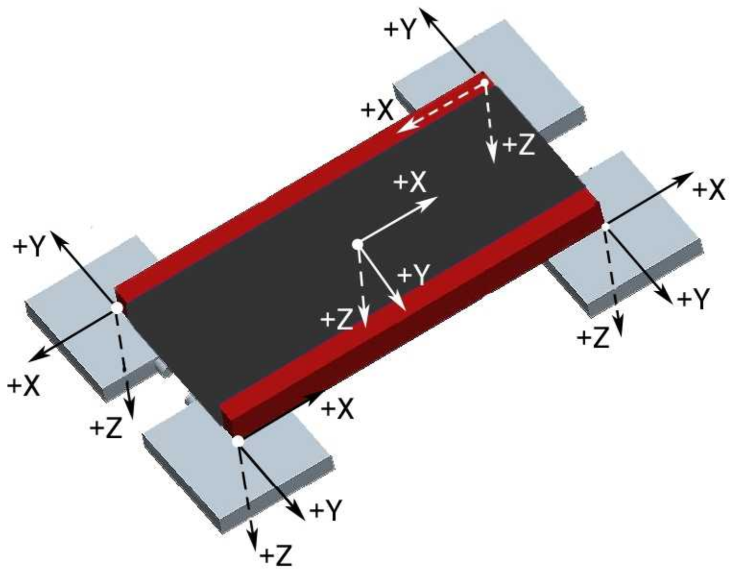



**Figure 6. Four 46.2 x 50.8 cm force plates were mounted to each corner support structure of the treadmill**

The primary ground reaction force variable of interest was the peak impact force during ground contact. The motion analysis system was used to record 3-dimensional trajectories of reflective markers, 51 in total, which was a modified Plug-in-Gait marker set (Figure 7 and Figure 8), attached to each body segment of the subjects. Eventually, the results of the time series motion analysis will be combined with suit engineering data on joint forces and torques to estimate the magnitude and degree of resistive exercise associated with walking EVAs in partial gravity.

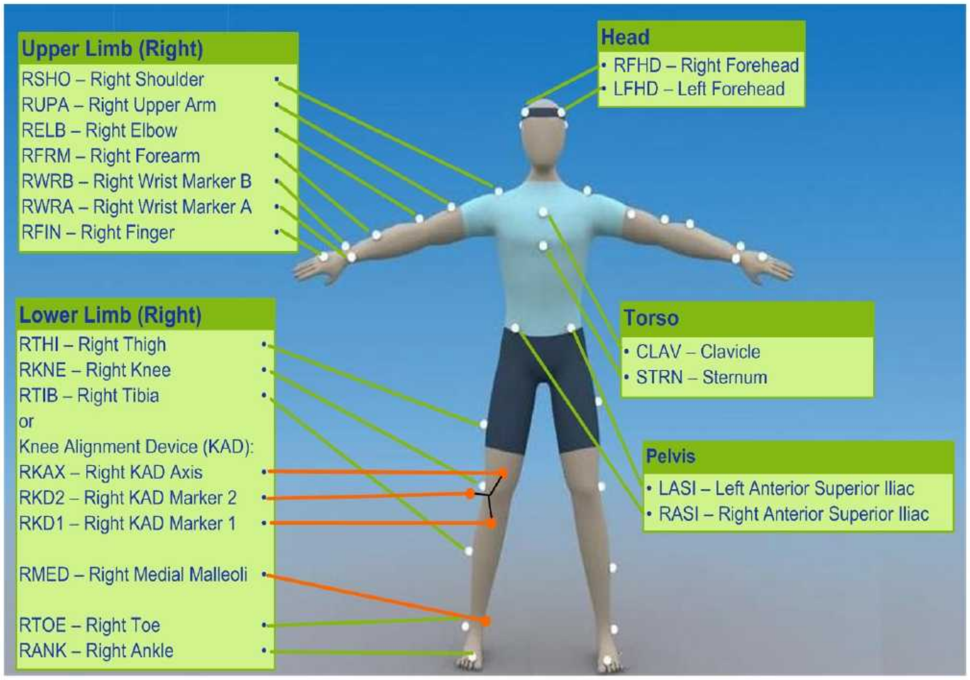



**Figure 7. Anterior view of Plug-in-Gait marker set**

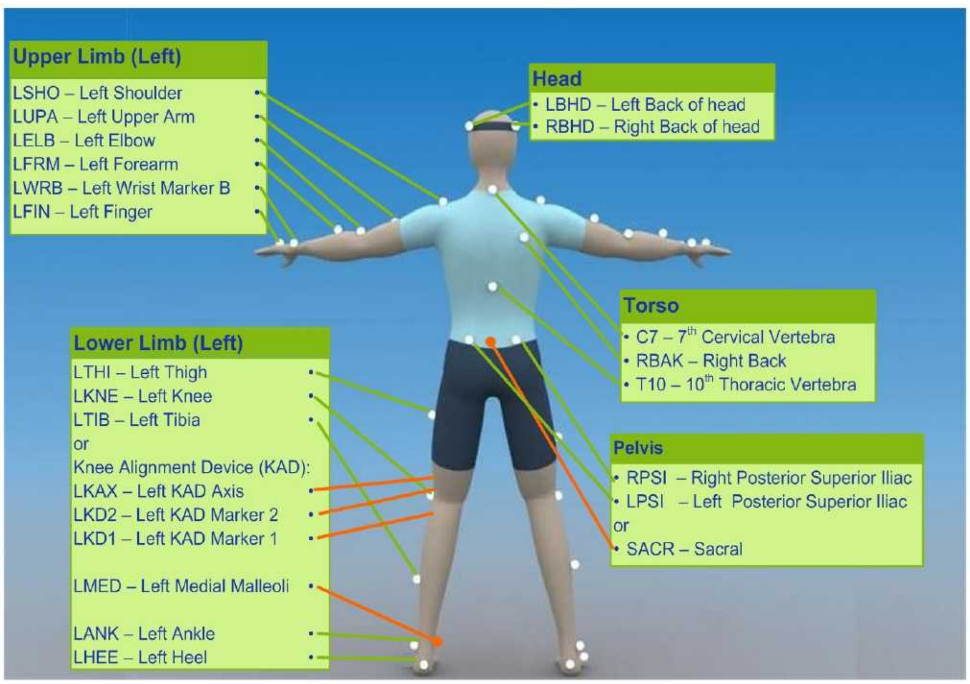



**Figure 8. Posterior view of Plug-in-Gait marker set**

In movements such as locomotion, the motions of the segments are cyclic in nature. More specifically, walking is the periodic movement of each foot from one position of support to the next. For walking, one stride (or cycle) is defined as the distance traveled by a person from one heel strike to the next heel strike on the same side. A tool that is commonly used to transform periodic cycles to a traditional linear system is known as Floquet's theory**.** Simply, Floquet's theorem uses ordinary differential equations to convert a periodic function into traditional linear function. The end results of Floquet's theorem are eigenvalues, ranging between 0 and 1, of the mathematical matrix that defines the linear system. In gait studies, this eigenvalue is often used as a measure of stability (Cheng & Lin, 1995). Since there are many gait cycles during walking the maximum eigenvalue is identified. The maximum eigenvalue is used as an overall stability measure because it is the value that dominates the dynamic system. In other words, the closer the maximum eigenvalue is to the value of 1, the less stable the person is walking and the longer it takes the individual to return to steady state locomotion. If the maximum eigenvalue exceeds the value of 1, then the person has become so unstable that they have fallen or tripped. However, in the case of the walkback test, the POGO will not allow a crewmember to fall for obvious safety reasons. For purposes of gait analysis in this report, we will use the term Floquet multiplier as a more specific name for the eigenvalue derived from the Floquet's analysis.

Location of CG was determined by from a computer-aided design (CAD) model of the test subject using ProE Wildfire 2.0. A standard 182.9 cm, 81.6 kg (72 inch, 180 lb) human CAD model was adjusted for height and then the density was set so that the mass equaled the mass of the real test subject. The stinger (fore/aft positioning) and spider (up/down positioning) CAD models were set to the numbers used by the subject. The CAD analyzed for overall system CG location and that was compared to the position of the gimbal center, the point at which all 3 gimbal rotation axes—the overhead suspension line (yaw axis), the pivot axis between upper and lower tube frames (pitch axis), and the stinger rotation axis (roll axis)—intersect. The distance between the overall system CG and the gimbal center was recorded for each subject. The distance between the overall system CG and the subject's CG was calculated only for the standard human model.

**Subjective Data Collection**

For the unsuited and suited energy-velocity test sessions the Rating of Perceived Exertion (RPE; Borg, 1982), Gravity Compensation and Performance Scale (GCPS) and body discomfort (Corlett & Bishop, 1976) ratings were recorded at the end of each stage. The RPE is used to gauge how much effort a person feels they must exert to perform a task, particularly exercise, on a scale of 6 to 20 developed to correlate roughly with 1/10 heart rate. The GCPS, with ratings of 1 to 10, is used to determine the level of compensation a person feels is necessary to perform and complete a given task in an altered gravity environment compared to the performance of that same task unsuited in 1 *g*. This is a new scale that was modified from the original Cooper-Harper scale, which was developed for pilot controllability of an aircraft (Cooper, 1957; Cooper & Harper, 1969). Because it is a new scale and used only for specific testing, the GCPS has not yet been validated in other studies. By showing the relationship of the GCPS ratings to other validated objective variables, the test team hopes to demonstrate the utility of this new scale. The body discomfort scale (0 to 10) by Corlett & Bishop was used to rate discomfort on any and all portion(s) of the body.

Before beginning the 10-km test, subjects completed the first phase of the NASA Task Load Index (TLX) questionnaire (Hart & Staveland, 1988), which measures the perceived physical and mental workload necessary to perform a given task. For the NASA TLX, 6 rating scales are used to evaluate a task: mental demand, physical demand, temporal demand, performance, effort, and frustration level. A pair-wise comparison of the scales is completed to determine which 2 scales have the most impact to the workload. Each scale is then rated from 0% to 100% to assess how much that scale contributed to the overall workload. Using the results from the pair-wise comparisons to weight each scale, a weighted mean workload score is generated, 0% to 100% (100% = highest workload).

At the start of the 10-km test, the subject then donned the suit and, once operating pressure was reached, was asked to complete a task consisting of tracking targets on a touchpad as quickly as possible. During the walkback portion of test, subjects were prompted for RPE, GCPS, and discomfort ratings every 15 minutes. At the end of the 10-km walkback session, subjects completed final RPE and NASA TLX workload ratings as well as a final target tracking. For the NASA TLX, all of the factors are scored from 0 to 100, except for performance, which is scored from 100 to 0. Therefore, a low performance score is good. Scales used for these measurements are presented in Appendix C.

In an analog such as the POGO, there are many options to collect objective data such as metabolic rate or ground-reaction force, but in many other analogs, there is a very limited amount of objective data that can be collected. In these other analogs with limited objective data options, subjective data can readily be collected. It is important then to correlate the subjective data to objective data whenever the opportunity exists. Scales such as the RPE and GCPS provide a glimpse into the level of effort and compensation a subject must exert and, in some cases, may be the only data available to collect. As much as possible, the relationships between subjective measurements and key metrics such as metabolic rate must be established to allow for the assessment of the potential implications to objective measurements when test environments do not allow for various forms of objective data collection.

**Imaging**

Photographic data also were collected after completion of each testing run if human-suit interactions were unfavorable or resulted in skin or musculoskeletal abnormalities. This information will be provided as feedback to Space Medicine and the suit designers. During all suited tests, 2 Sony digital video cameras captured lateral (side) and anterior (front) video as well as auditory comments of the crewmember and test team, except during time periods declared to be private medical conferences by the medical officer.

# Results

## *Determination of PTS*

Both suited and unsuited PTS increased as gravity increased, but the effects were more pronounced while unsuited (Table 4). In lunar gravity, the PTS was higher in the suit but the opposite was seen in Mars gravity.

**Table 4. Unsuited and suited PTS as a function of gravity**

| | Unsuited PTS and Froude | | | | | | | | | Suited PTS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 *g* | | | 1/6 *g* | | | 3/8 *g* | | | 1/6 *g* | | 3/8 *g* | |
| Subject | PTS $m{\cdot}s^{-1}$ | PTS mph | Froude | PTS $m{\cdot}s^{-1}$ | PTS mph | Froude | PTS $m{\cdot}s^{-1}$ | PTS mph | Froude | PTS $m{\cdot}s^{-1}$ | PTS mph | PTS $m{\cdot}s^{-1}$ | PTS mph |
| **1** | 2.15 | 4.8 | 0.46 | 1.12 | 2.5 | 0.77 | 1.56 | 3.5 | 0.65 | 1.25 | 2.8 | 1.65 | 3.7 |
| **2** | 2.01 | 4.5 | 0.45 | 1.52 | 3.4 | 1.56 | 1.79 | 4.0 | 0.94 | 1.74 | 3.9 | 1.70 | 3.8 |
| **3** | 2.19 | 4.9 | 0.48 | 1.43 | 3.2 | 1.28 | 1.79 | 4.0 | 0.85 | 1.43 | 3.2 | 1.34 | 3.0 |
| **4** | 2.06 | 4.6 | 0.50 | 1.34 | 3.0 | 1.29 | 1.88 | 4.2 | 1.15 | 1.25 | 2.8 | 1.70 | 3.8 |
| **5** | 2.19 | 4.9 | 0.55 | 1.34 | 3.0 | 1.19 | 1.83 | 4.1 | 1.04 | 1.43 | 3.2 | 1.39 | 3.1 |
| **6** | 2.01 | 4.5 | 0.43 | 1.30 | 2.9 | 1.09 | 1.56 | 3.5 | 0.71 | 1.48 | 3.3 | 1.48 | 3.3 |
| Avg ± SD | 2.10 ± 0.08 | 4.7 ± 0.2 | 0.48 ± 0.04 | 1.34 ± 0.14 | 3.0 ± 0.3 | 1.2 ± 0.26 | 1.74 ± 0.14 | 3.9 ± 0.3 | 0.89 ± 0.19 | 1.43 ± 0.18 | 3.2 ± 0.4 | 1.54 ± 0.16 | 3.5 ± 0.4 |

For both lunar and Martian gravity, the PTS did not agree with a predicted Froude number of 0.5 (Alexander, 1999), whereas ambulation in 1 *g* was consistent with this prediction. Froude numbers were not calculated for suited ambulation.

## *Location of System Center of Gravity*

When assessing at CG effects, there are 2 primary areas in question. The first is how the system CG lines up with the gimbal axes of rotation and the second is how the system CG differs from the subject's CG. Looking at the first area in question, the location of the total system CG from the gimbal center of rotation averaged 1.8 ± 0.87 cm forward and 1.34 ± 0.86 cm low. As seen in Figure 9, all subjects selected this slight misalignment between the system CG and gimbal center of rotation that was forward and low.

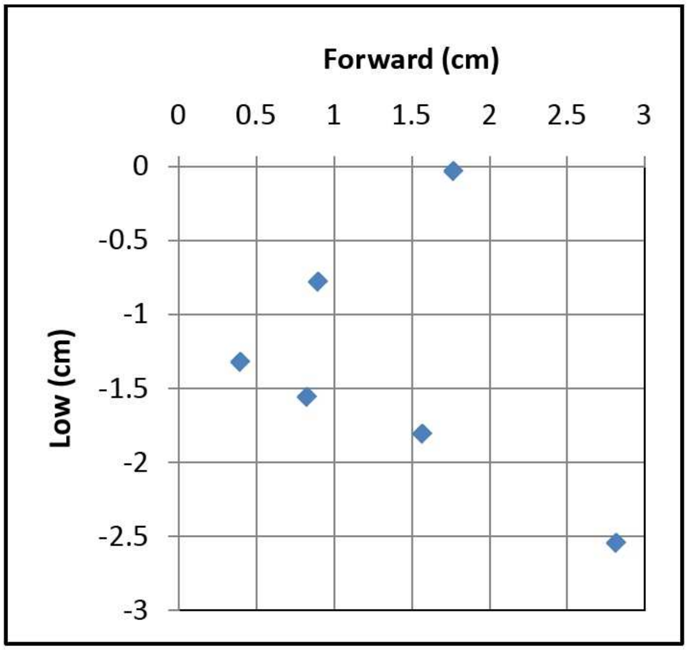



**Figure 9. Total system center of gravity location in relation to gimbal center of rotation**

Looking at the second question, how the total system CG differs from the subject's CG, post-test analyses indicated that the this differences was 11.0 cm aft and 20.1 cm high when compared to the CG of a standard 182.9 cm, 81.6 kg CAD modeled subject. This would vary subject to subject depending on the location of their CG as compared to the CAD modeled subject.

## *Metabolic and Transport Costs of Locomotion*

In most cases, subjects were able to complete the prescribed 3 walking and 3 running speeds in all conditions, with the exception of the Mars suited condition. There were some isolated cases at low POGO offloads where oscillations would develop in the spreader bar assembly at certain speeds and those speeds had to be skipped. In all instances, suited locomotion required higher metabolic rates than unsuited at the same gravity level.

The various lunar conditions are compared to the 1-*g* unsuited baseline Figure 10. The metabolic rates of suited walking in simulated lunar gravity are significantly higher than unsuited walking in Earth gravity. Metabolic differences between these conditions decreased with increased speed, and intersected at approximately 2.3 m•s$^{-1}$ (5.1 mph), above which metabolic rates for suited running in simulated lunar gravity trended lower than unsuited running in Earth gravity.

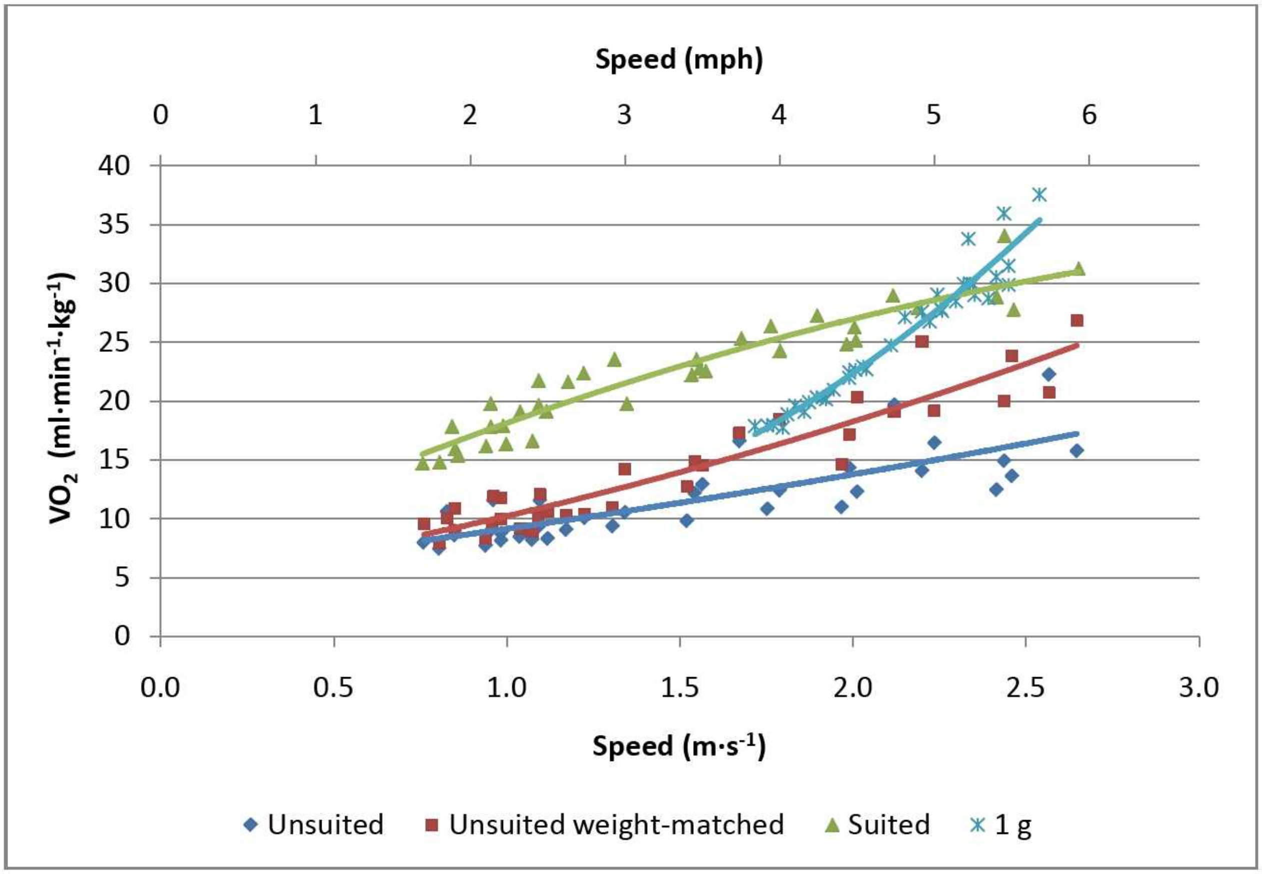



**Figure 10. Metabolic rates of lunar locomotion compared to Earth unsuited**

It was theorized that the metabolic cost of the suit due to the increased weight could be considered to be the difference between the lunar-unsuited baseline as compared to the unsuited weight-matched trials. This comparison can only account for a change in weight and would not account for additional metabolic cost associated with the increased mass needed to get to this weight. These unaccounted factors include inertia, CG, and mass distribution differences. At walking speeds, this difference was less than 3.5 ml•min$^{-1}$•kg$^{-1}$, but steadily increased as speed increased. At the highest speeds, the average metabolic cost of the added weight was approximately 7.0 ml•min$^{-1}$•kg$^{-1}$. The metabolic cost of the suit unrelated to weight could be considered to be determined by comparison of the suited results to the unsuited weight-matched controls. This difference was determined to be relatively constant at approximately 8.0 ml•min$^{-1}$•kg$^{-1}$, representing approximately 18% of the average $VO_2$pk of the subject group.

Figure 11 depicts the metabolic cost of simulated Mars gravity locomotion compared to Earth unsuited conditions. As with lunar conditions, the metabolic costs of Martian walking are significantly higher than walking on Earth. Mars-suited metabolic rates increased at a much higher rate in Martian than in lunar gravity, with subjects approaching the grouped average $VO_2$pk at only 1.5 m•s$^{-1}$. In lunar gravity, the metabolic cost of the suit unrelated to weight was generally constant (~8 ml•min$^{-1}$•kg$^{-1}$) over the full range of speeds from 0.76 to 2.65 m•s$^{-1}$. However, for Mars, even small increases in walking speed produced dramatically elevated nonweight related suited metabolic costs, from ~14 to 24 ml•min$^{-1}$•kg$^{-1}$ over a small range of speeds (1.07 to 1.53 m•s$^{-1}$).

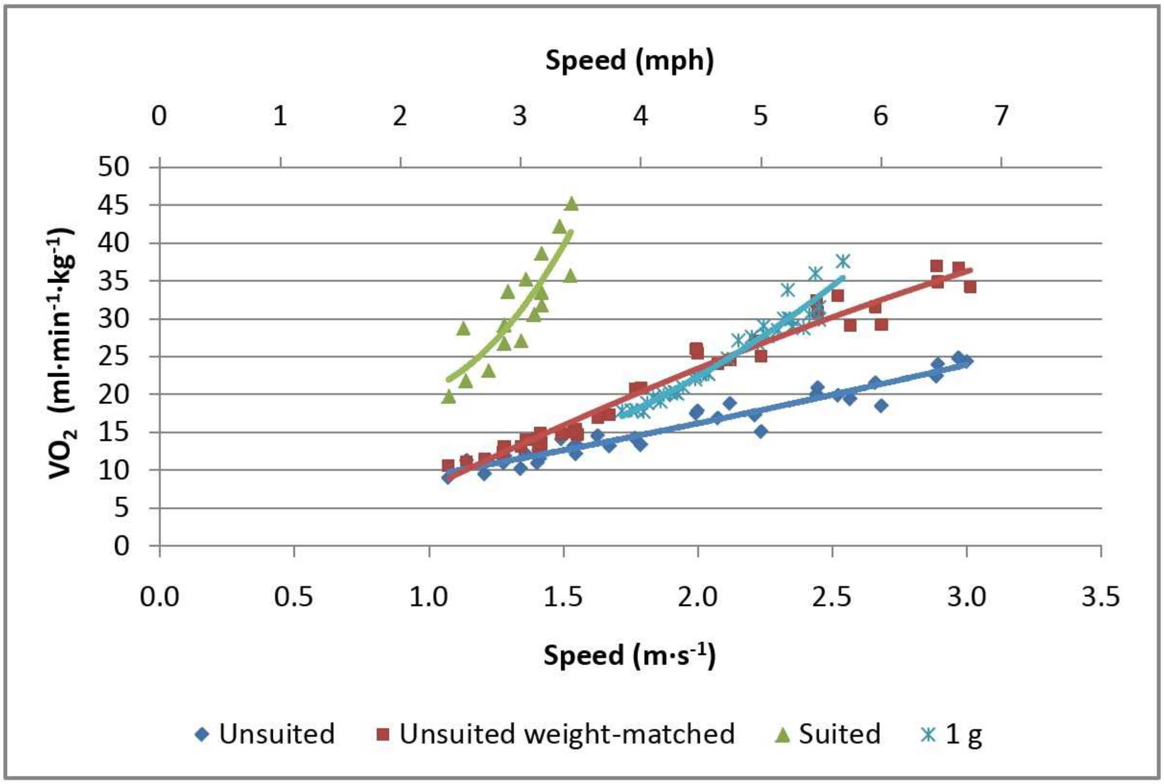



**Figure 11. Metabolic rates of Mars locomotion compared to Earth unsuited**

Table 5 summarizes the metabolic rate findings as related to transition speed position (Table 3). During lunar gravity, the total metabolic cost of the suit increased as speed increased. Of the factors that contributed to the metabolic cost of the suit, the cost of weight increased with speed, but the cost of the other factors did not vary with speed. At Mars gravity, the total metabolic cost of the suit was at least twice that of lunar gravity, but this was mostly due to the other factors as the cost of weight was very similar to lunar gravity.

**Table 5. Metabolic rate summary for lunar and Martian ambulation**

| | | $VO_2$ (ml·min$^{-1}$·kg$^{-1}$) | | | | | | % $VO_2$ | |
|---|---|---|---|---|---|---|---|---|---|
| Gravity | Speed | Unsuited | Unsuited Weight-Matched | Suited | Total Metabolic Cost of Suit | Metabolic Cost Due to Weight | Metabolic Cost Due to Other Factors | Metabolic Cost Due to Weight | Metabolic Cost Due to Other Factors |
| 1/6 *g* | 1 | 8.8 | 9.2 | 16.7 | 8.0 | 0.4 | 7.6 | 5% | 95% |
| | 2 | 9.1 | 10.3 | 18.4 | 9.4 | 1.2 | 8.2 | 13% | 87% |
| | 3 | 9.4 | 10.8 | 20.0 | 10.6 | 1.4 | 9.2 | 13% | 87% |
| | 4 | 12.4 | 14.7 | 22.7 | 10.3 | 2.3 | 8.0 | 23% | 77% |
| | 5 | 14.0 | 19.1 | 25.7 | 11.8 | 5.2 | 6.6 | 44% | 56% |
| | 6 | 16.6 | 22.1 | 29.3 | 12.7 | 5.5 | 7.1 | 44% | 56% |
| 3/8 *g* | 1 | 11.0 | 12.7 | 27.6 | 16.5 | 1.7 | 14.9 | 10% | 90% |
| | 2 | 12.1 | 13.7 | 32.5 | 20.4 | 1.6 | 18.8 | 8% | 92% |
| | 3 | 12.1 | 14.1 | 35.7 | 23.6 | 2.0 | 21.6 | 9% | 91% |

Figure 12 shows the lunar $O_2$ transport cost, which is a measure of the $O_2$ required to move 1 kg a distance of 1 km, providing an index of efficiency with lower transport cost indicating increased efficiency. The transport cost of lunar walking at speeds less than 1.5 m•s$^{-1}$ (3.4 mph) was highest for suited conditions. The cost was similar for the lunar unsuited and unsuited weight-matched conditions. Data was not obtained in this study across a full range of 1-*g* conditions however, using the American College of Sports Medicine (ACSM) predictive equations, the 1-*g* predictive transport cost for slower walking speeds would be very similar to the lunar-unsuited trials (ACSM, 2006). In all lunar cases, transport cost decreased with increased speed up to 2.0 m•s$^{-1}$. After that, the unsuited conditions were level and began to increase at 2.2 m•s$^{-1}$, however, the suited transport costs continued to improve with increasing speed up to the limits of our test at 2.7 m•s$^{-1}$. At speeds greater than 2.3 m•s$^{-1}$, suited $O_2$ transport cost was lower than unsuited running in Earth gravity.

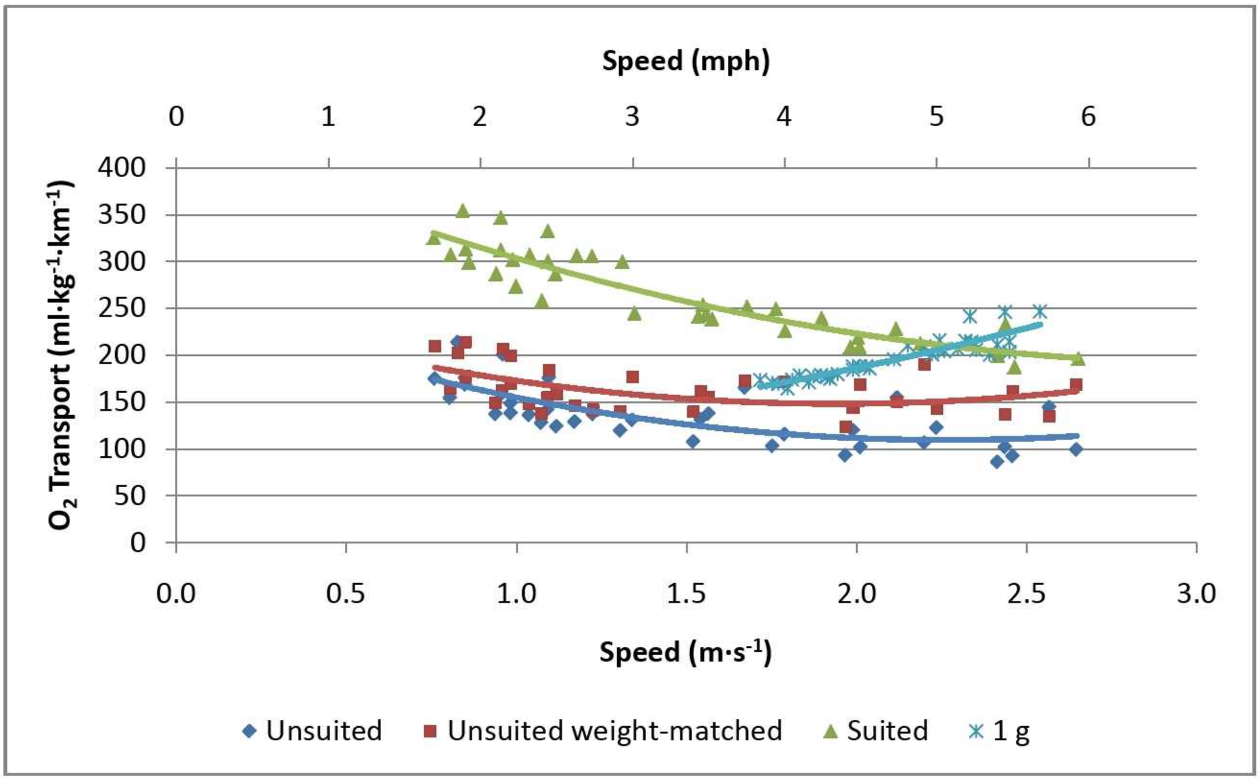



**Figure 12. Transport cost of lunar locomotion compared to Earth unsuited**

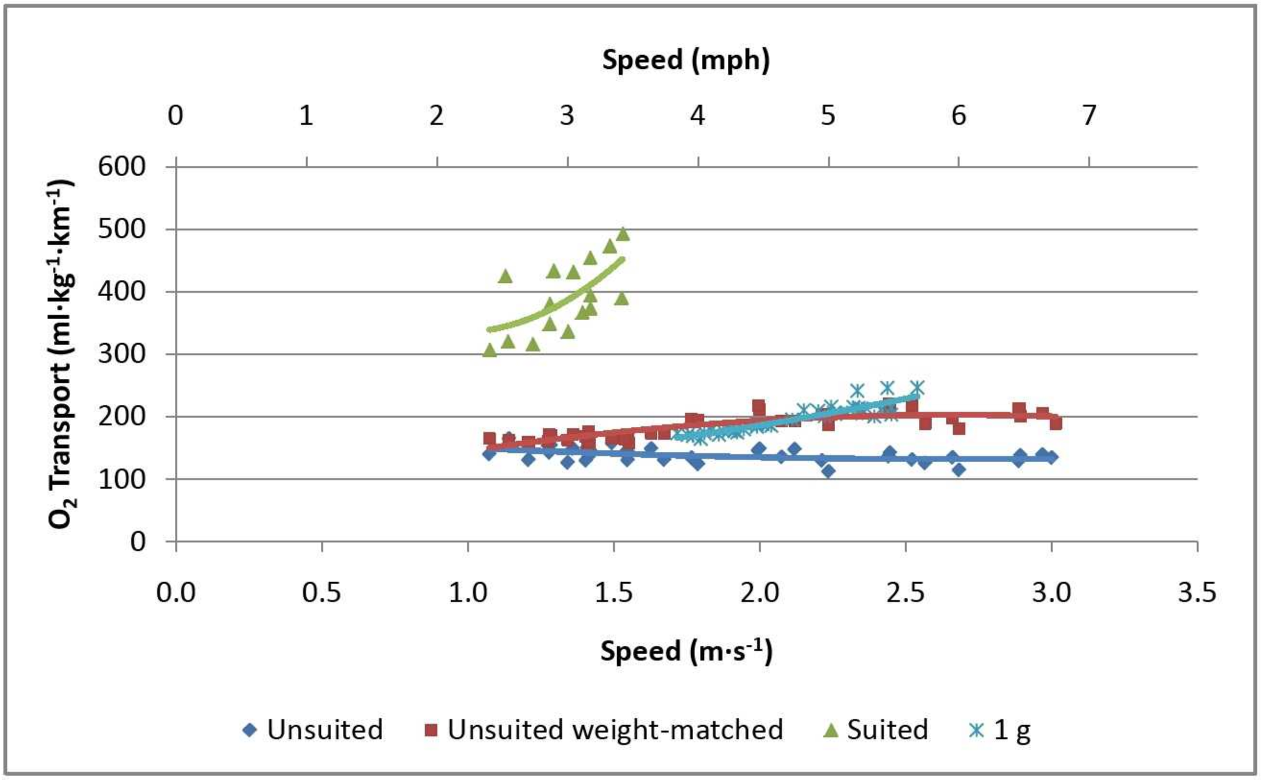



**Figure 13. Transport cost of Mars locomotion compared to Earth unsuited**

$O_2$ transport costs during Mars gravity conditions are shown in Figure 13. Unsuited Martian transport cost slightly decreased with speed unlike the larger drop seen with the unsuited lunar conditions. Mars-unsuited weight-matched transport cost increased with speed, leveling off at approximately 2.0 m•s$^{-1}$, unlike the lunar unsuited weight-matched condition, which initially decreased and then leveled off at 1.5 m•s$^{-1}$. In the suited condition, transport cost started high and sharply increased with speed, in marked contrast to the lunar-suited condition, which decreased with increased speed.

Figure 14 shows the waist joint cycles and suited metabolic rates as a function of speed for lunar and Martian gravities. Waist joint cycles were calculated as any deviation from the midline as defined during a pretest static trial. The increase in waist cycles closely followed the increase in metabolic rate at each gravity level with much steeper slopes for Mars than for lunar conditions. For lunar ambulation, the waist cycles increased reaching a maximum of 54 cycles per minute at 2.5 m·s$^{-1}$. In Martian gravity, the waist joint cycles increased at a much greater rate reaching a maximum of 56 cycles per minute at 1.4 m•s$^{-1}$.

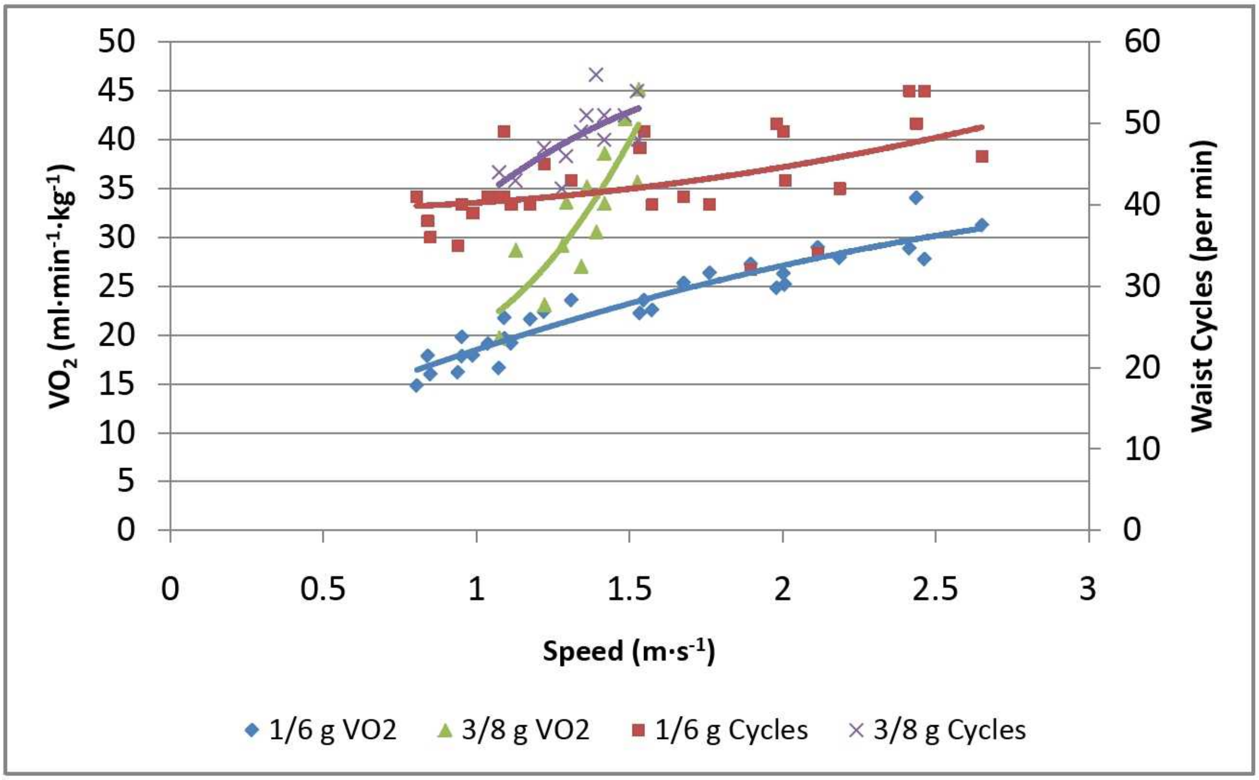



**Figure 14. Metabolic rate and waist cycles during suited treadmill locomotion at lunar and Martian gravity**

Figure 15 describes unsuited metabolic rates at varied gravity levels across different speeds. At speeds less than 1.3 m•s$^{-1}$, there was little difference between conditions, but as speed increased, metabolic rate slopes were greater as the gravity level increased.

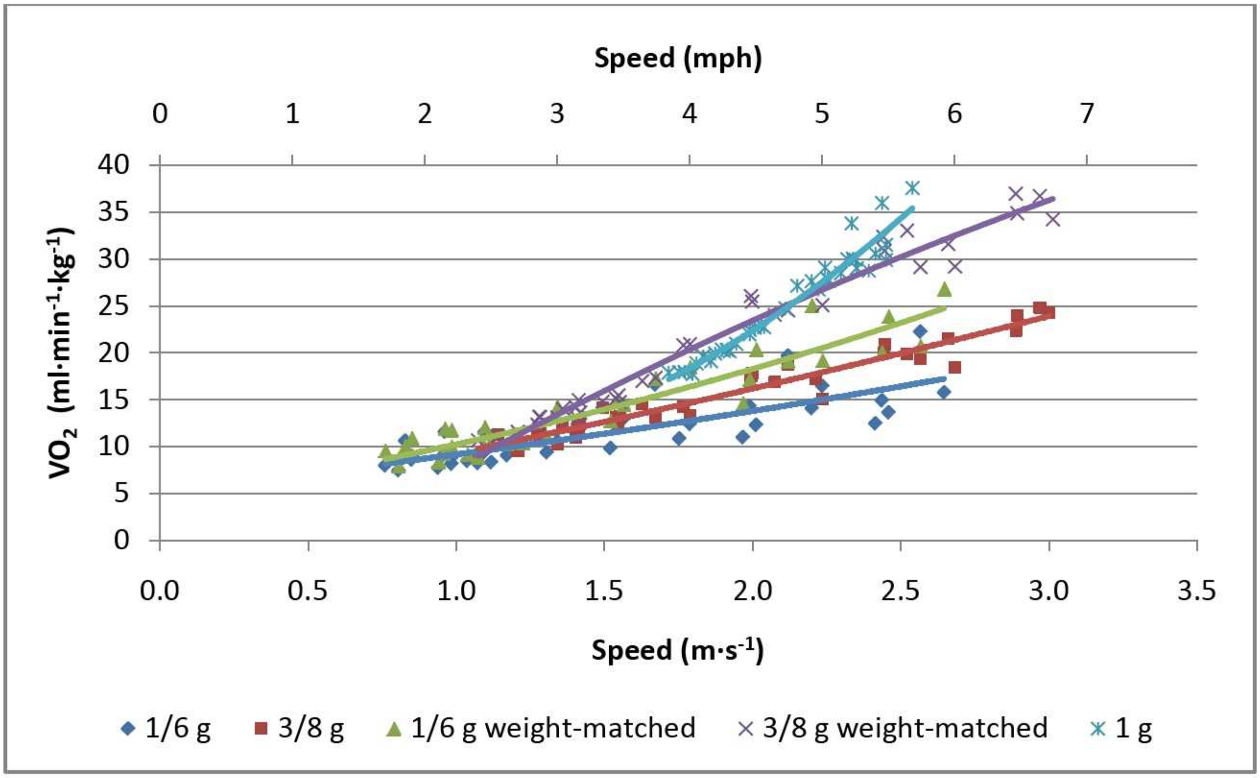



**Figure 15. Unsuited metabolic rate at varied gravity levels across different locomotion speeds**

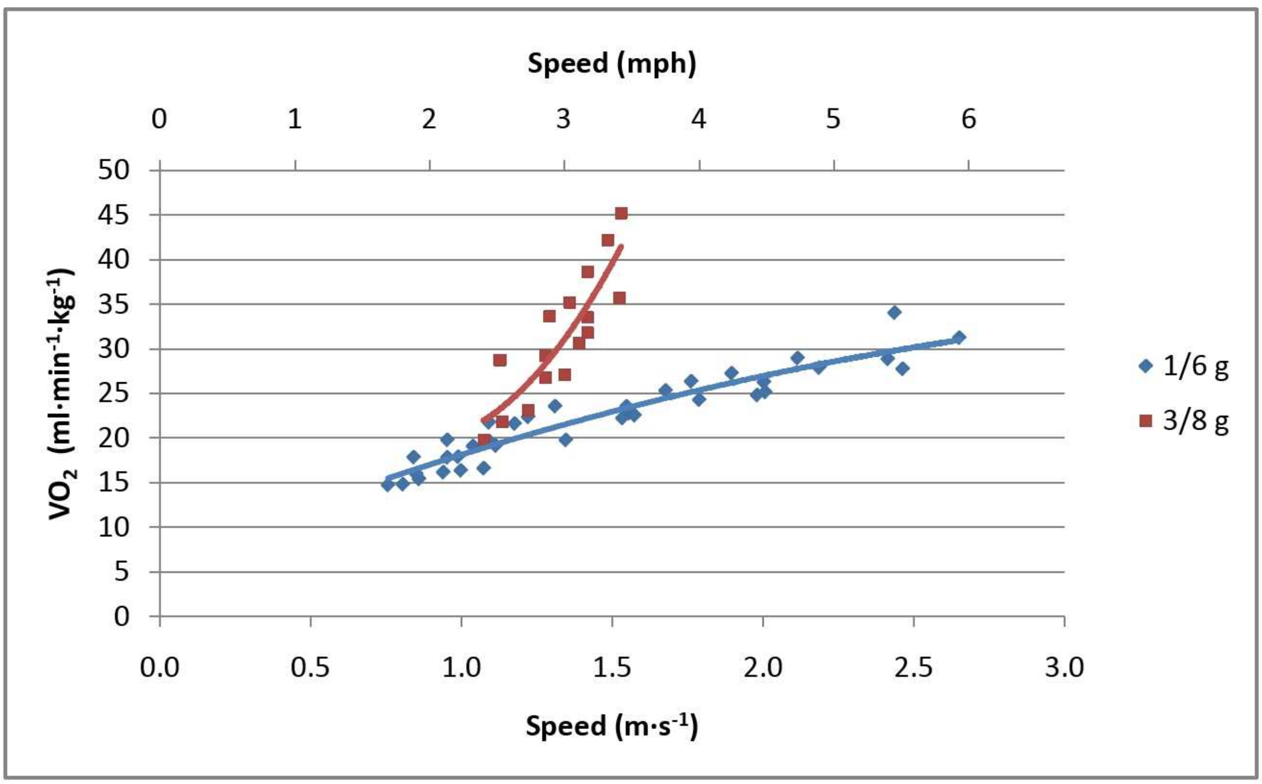



**Figure 16. Suited metabolic rates at varied gravity levels across different locomotion speeds**

Figure 16 compares suited metabolic rates of 1/6-*g* and 3/8-*g* conditions. At the slowest speed for the 3/8-*g* condition, the metabolic rate was similar to 1/6 *g*, but unlike the gradual slope of the 1/6-*g* condition, the 3/8-*g* condition increased so rapidly that all subjects could only complete 2 to 3 of the 6 expected velocities.

To understand if the combined metabolic rate trend line was representative of the subject pool, Figure 17 shows the individual metabolic rate responses at both lunar and Mars gravity and in the unsuited and suited conditions.

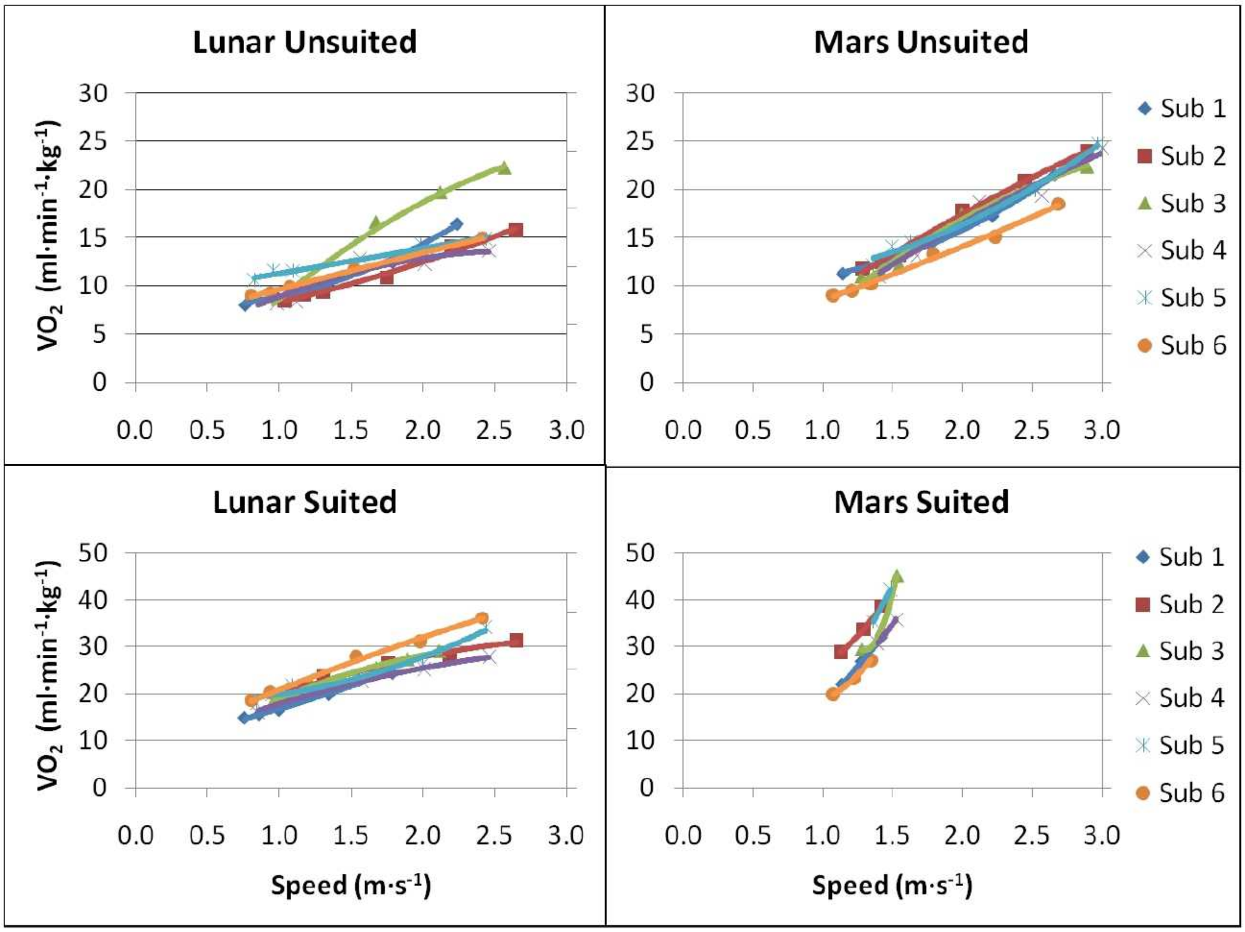



**Figure 17. Individual metabolic rates across different speeds at different gravity levels**

Outside of 1 subject having higher metabolic rates while running unsuited in 1/6 *g*, the 6 subjects tended to show very similar relationships.

## *Biomechanics of Locomotion*

Ground reaction force increased as a function of speed for all conditions (Figure 18 and Figure 19). To compare across all gravity levels, GRF is reported as body weights (BW), which are multiples of the subject's 1-*g* body weight. As a general trend, peak GRF also increased as a function of the total gravity adjusted weight (the sum of the subject and suit mass multiplied by the gravity level). For lunar gravity, the suited GRF was greater than the unsuited weighted GRF, but this trend was opposite at speeds greater than 2.1 m•s$^{-1}$. At Mars gravity, the suited GRF was consistently higher than the unsuited weighted condition. Comparing trends, lunar suited GRF was less than 1-*g* unsuited, whereas Mars suited GRF looked to be greater than 1-*g* unsuited.

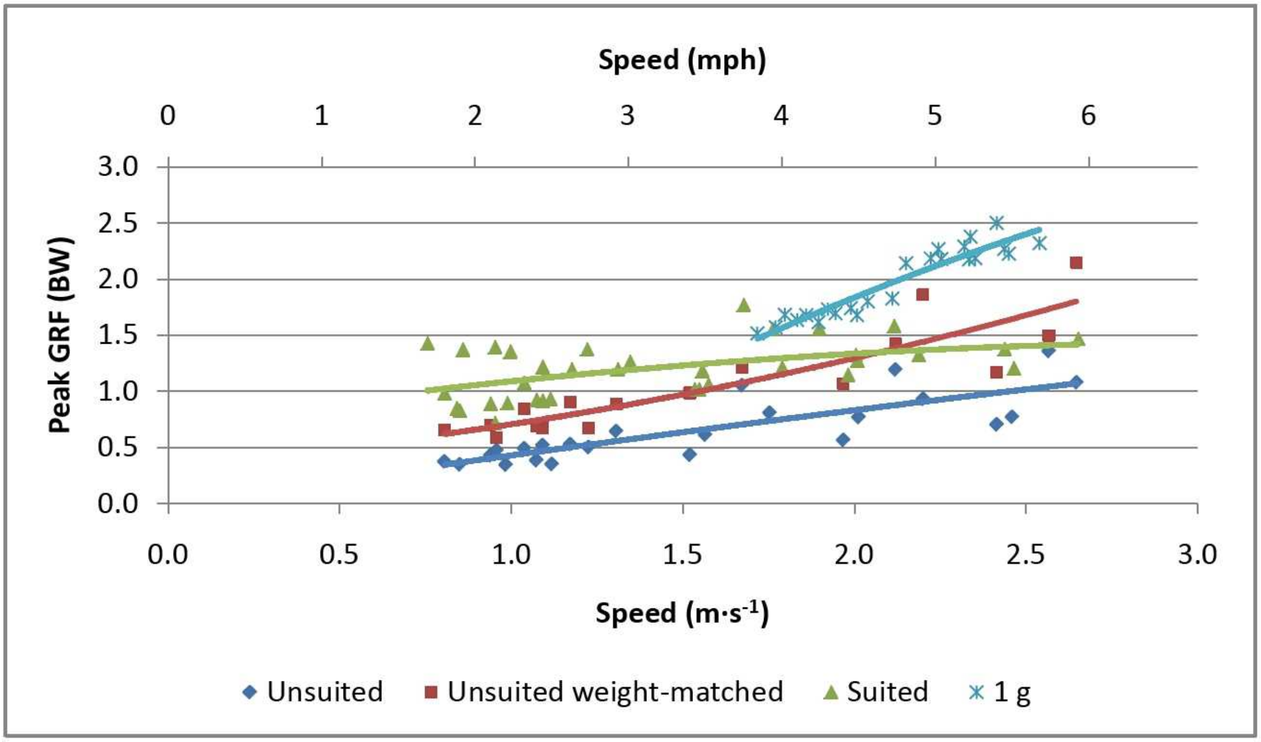



**Figure 18. Peak GRF of Lunar locomotion compared to Earth unsuited**

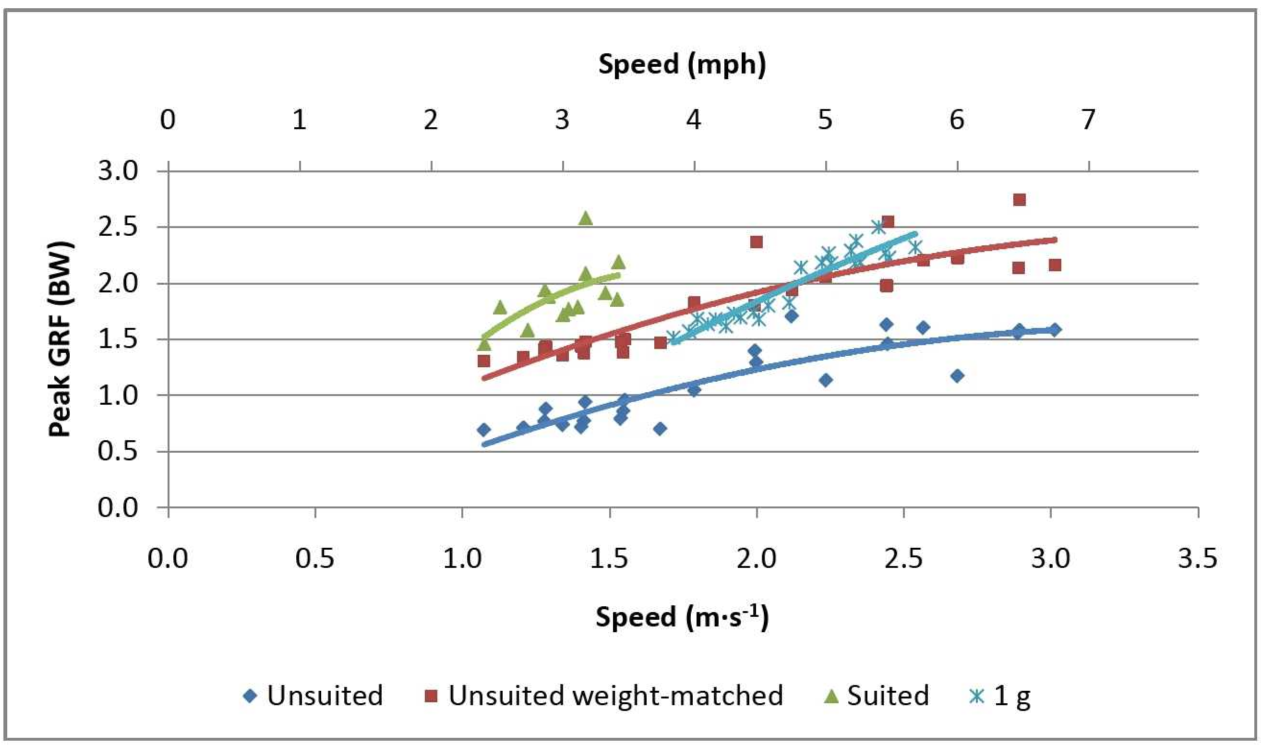



**Figure 19. Peak GRF during Mars locomotion compared with Earth unsuited**

Figure 20 shows the maximum Floquet multiplier as a function of velocity for all subjects in suited and unsuited conditions. There is a general but inconsistent trend toward increased stability with increasing velocity, and decreased stability in suited versus unsuited conditions.

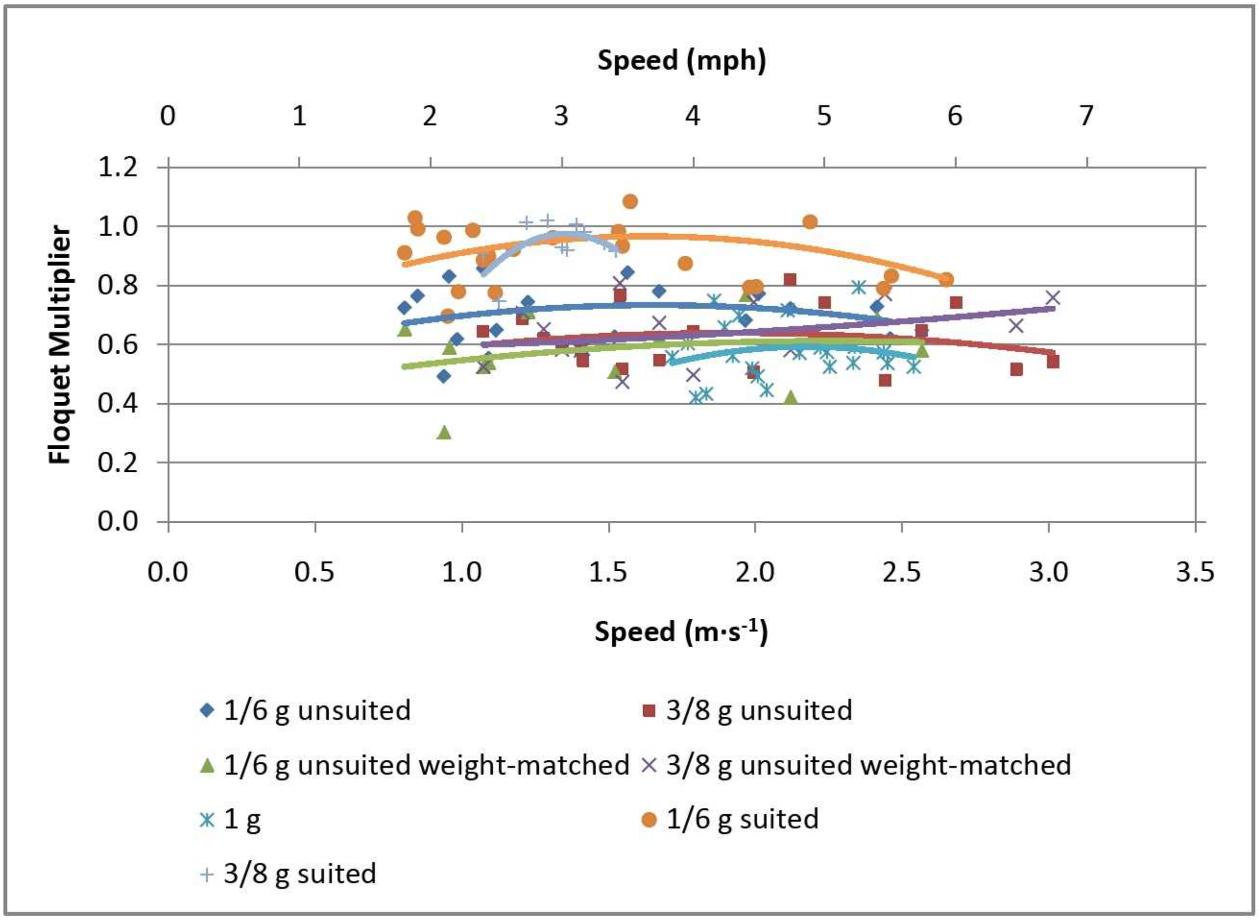



**Figure 20. Maximum Floquet multiplier for all conditions**

## *Subjective Factors of Locomotion*

In both lunar (Figure 21) and Mars conditions (Figure 22), suited gravity compensation and performance scale (GCPS) ratings were higher than both unsuited conditions. In lunar conditions, there was little difference between unsuited and unsuited weight-matched GCPS ratings, but in Mars gravity, the unsuited weight-matched conditions were consistently higher the unsuited condition. All unsuited conditions, with the exception of a few test points within the Mars weighted condition, were considered acceptable (GCPS $\leq 3$), but there were many instances of a GCPS rating indicating that improvement was warranted (GCPS of 4 to 6). With lunar suited conditions, the GCPS increased as speed increased indicating that improvement was warranted especially at higher speeds, although many points were still in the acceptable range. Mars suited conditions had the highest GCPS and were never in the acceptable range with GCPS ratings ranging from deficiencies warranting improvement to those that required improvement.

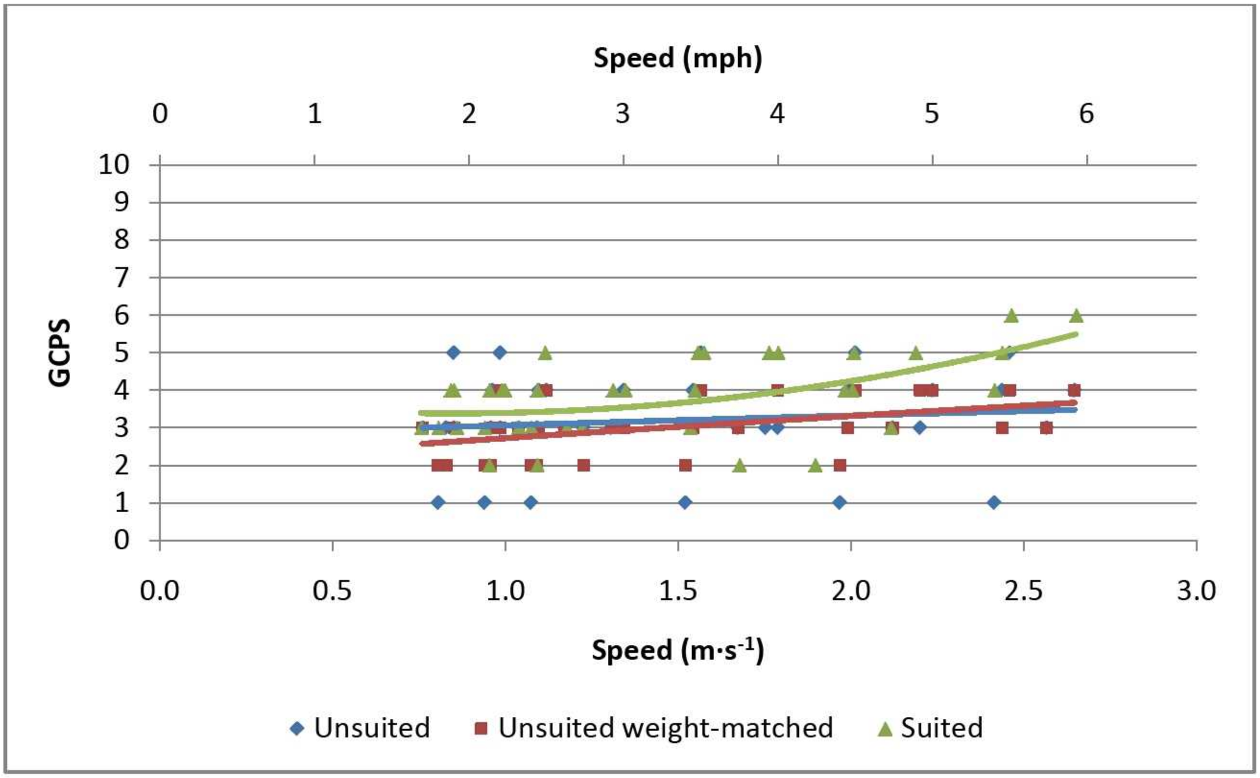



**Figure 21. GCPS rating as a function of speed at lunar gravity**

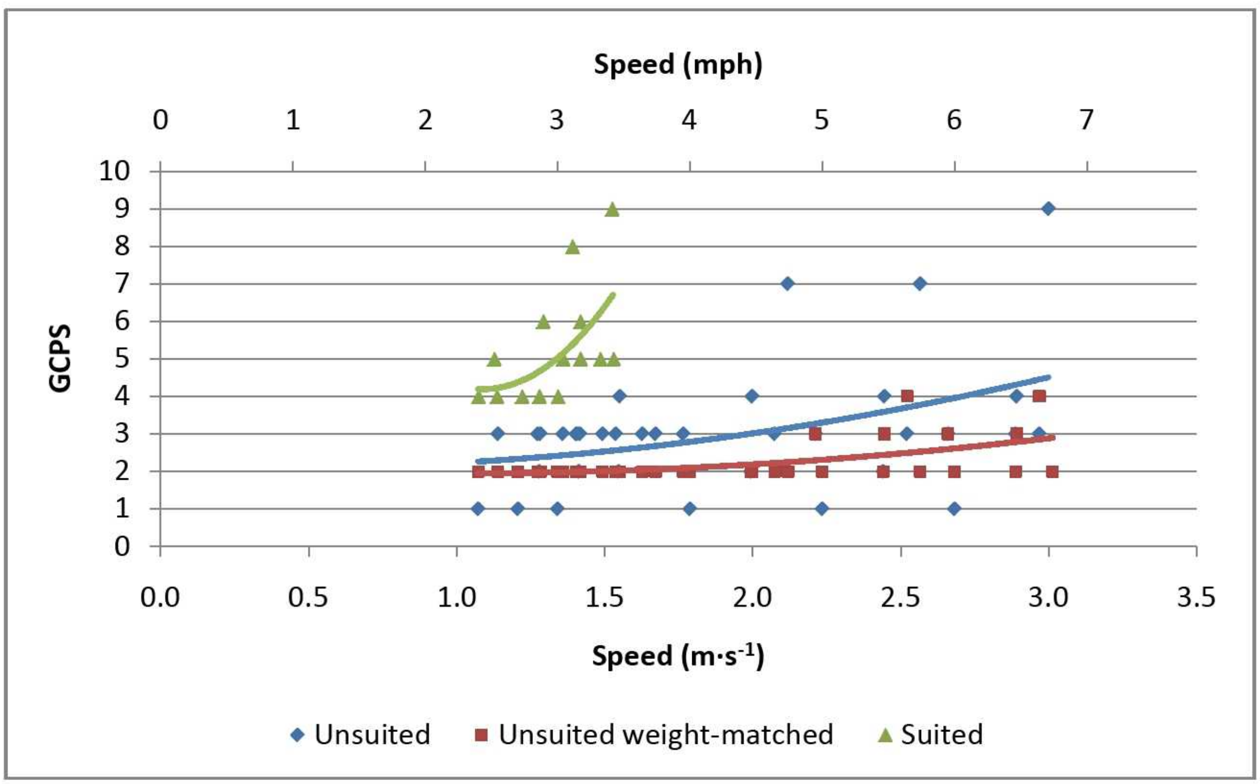



**Figure 22. GCPS rating as a function of speed at Mars gravity**

The RPE ratings for the lunar and 1-*g* conditions are shown in Figure 23. The RPE ratings are consistent with the objective metabolic measurements, demonstrating a trend of increased RPE with speed, and generally higher ratings for suited versus unsuited locomotion. At speeds above 2.0 m•s$^{-1}$, the lunar-suited RPE ratings were very similar to the unsuited 1-*g* control, although the metabolic rate for these 2 conditions did not show that same similarity (Figure 10).

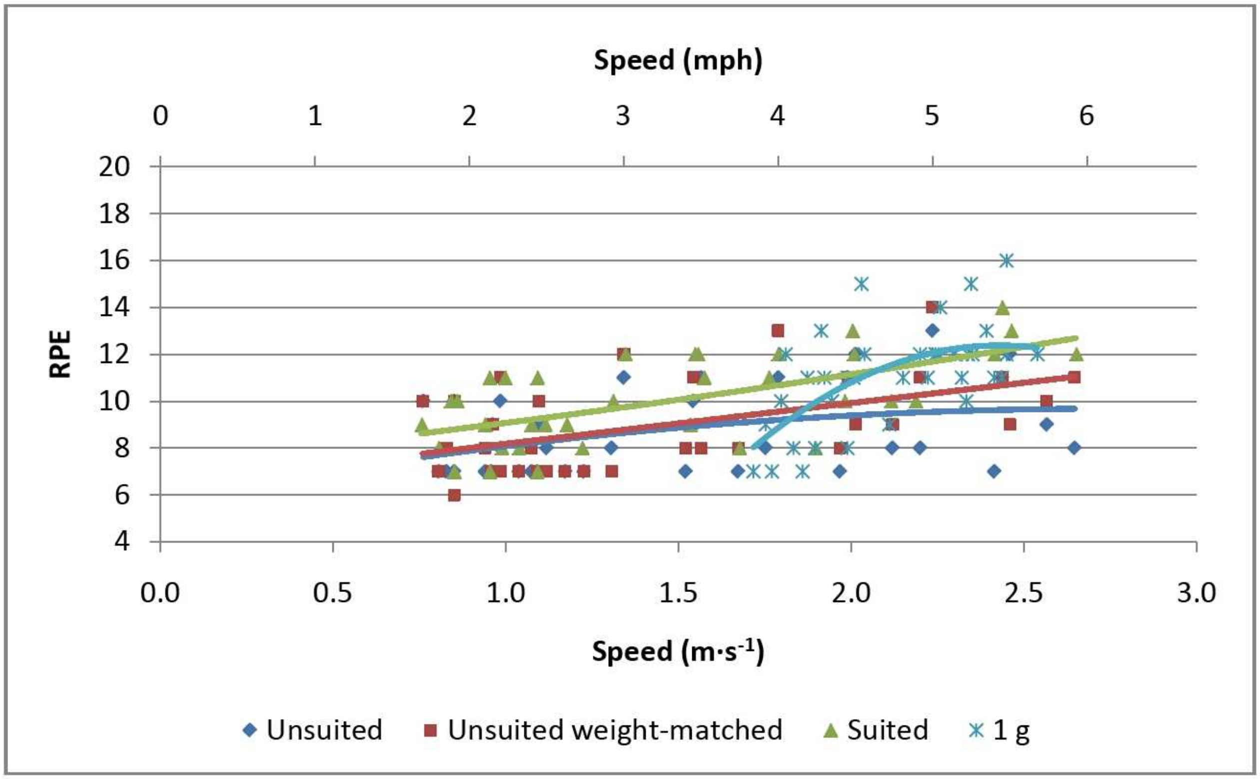



**Figure 23. RPE as a function of speed at Moon gravity compared to Earth conditions**

RPE ratings for Mars and l-*g* conditions are shown in Figure 24. RPE ratings again were consistent with metabolic data with an increase in RPE with speed and with suited RPE greater than unsuited conditions.

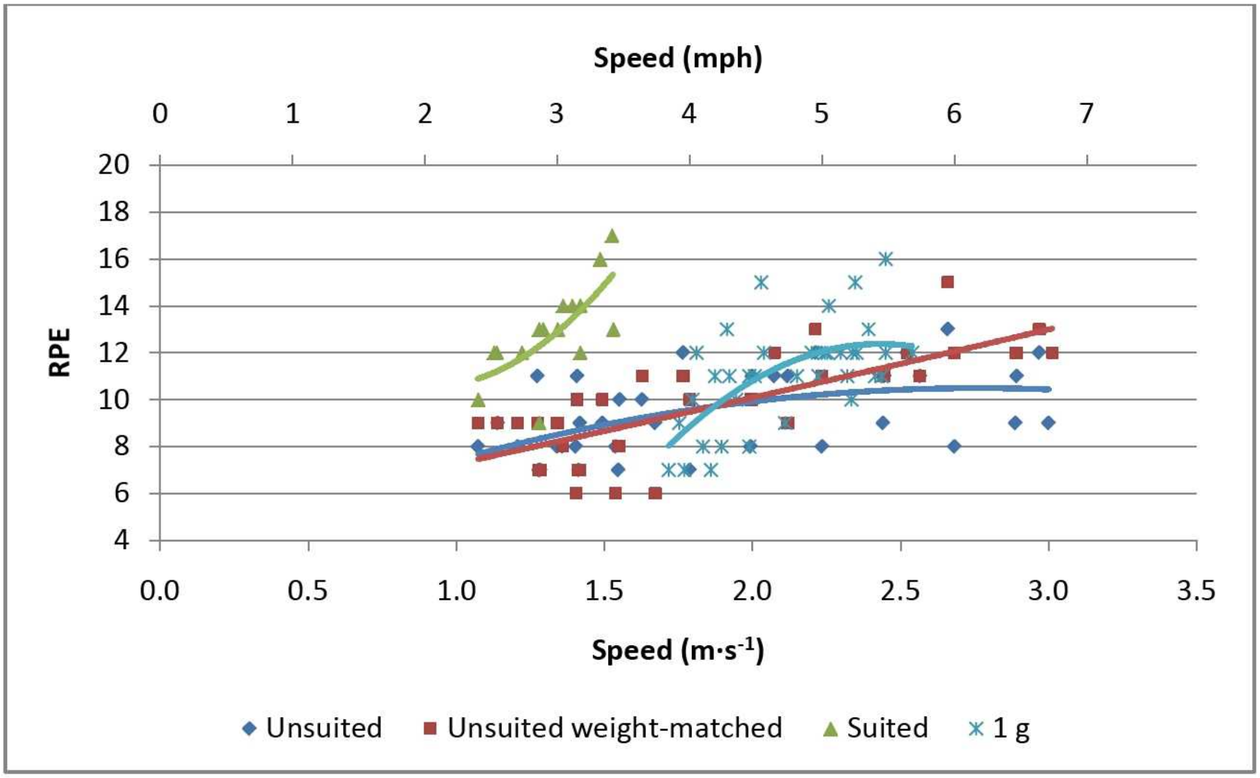



**Figure 24. RPE as a function of speed at Mars gravity compared to Earth conditions**

## *10-km Walkback Test*

The first finding of the 10-km portion of the test was that crewmembers could indeed ambulate 10 km in the MKIII suit at simulated lunar gravity, and did so without issue. The mean time to complete the 10 km was 96 minutes, at an average velocity of 1.74 m•s$^{-1}$ (3.9 mph) for the 6 subjects. The metabolic work level for the entire test averaged 51% of $VO_2$pk, with a range of 45% to 61%. Ratings of perceived exertion (11.8 ± 1.57 (Mean ± SD)) equated to a feeling between "light" (11) and "somewhat hard" (13) on the 6 to 20 point Borg RPE scale, indicating that subjective responses were similar to metabolic  responses. Similarly, subjects averaged 3.5 ± 1.44 (SD) on the 10-point Cooper-Harper scale, indicating "fair" to "moderate" operator compensation required to perform the task. These results for the walkback contingency and a comparison to nominal Apollo consumable usage are show in (Table 6).

**Table 6. Summary data for the lunar 10-km walkback portion of the test**

| 10k-Walkback Summary Data (averaged across entire 10 km unless noted) | | |
|---|---|---|
| | MEAN | SD |
| Avg. Walkback Velocity ($m \bullet s^{-1}$)<br>(mph) | 1.74<br>3.9 | 0.22<br>0.5 |
| Time to Complete 10k (min) | 95.8 | 13.0 |
| Avg. %$VO_2$pk | 50.8% | 6.1% |
| Avg. Absolute $VO_2$ ($l \bullet min^{-1}$) | 2.0 | 0.3 |
| Avg. Met rate (BTU/hr) | 2374.0 | 303.9 |
| *Max. 15-min-avg Met rate (BTU/hr)* | *2617.2* | *314.6* |
| Total Energy Expenditure (kcal) | 944.2 | 70.5 |
| Water used for drinking (oz) | ~24 to 32 | N/A |
| Water used for cooling (lb)* | 4.91 | N/A |
| $O_2$ Used (lb) | .635 lbs. | N/A |
| Planning / PLSS Sizing Data | Walkback | Apollo |
| $O_2$ Usage | 0.4 lbs/hr | 0.15lbs/hr |
| BTU average | 2374 BTU/hr | 933 BTU/hr |
| Cooling Water | 3.1 lbs/hr | 0.98lbs/hr |
| Energy Expenditure | 599 kcal/hr | 233 kcal/hr |

*assumes thermally neutral case and sublimator cooling

Looking at discomfort, the mean rating was 1.5 ± 1.1 (SD), "very low" to "low" on the 10-point Corlett and Bishop scale. The knee area and feet/toes were the most frequent sites of crewmember test and post-test complaints of discomfort associated with suit interaction. Other areas of discomfort less frequently reported were the Adam's apple (Velcro 'hook' rubbing), shoulders, elbow and thighs. Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles, and lower back.

Subjects' heat production rates ranged from 1918 to 2667 BTU/hour, averaging 2374 BTU/hour, a rate which would exceed the heat removal rates of the Apollo or Shuttle EVA suits (see Figure 26). Core temperature measurements indicated an average rise of 1 °C from normal (37 °C) across the entire test, although one subject's core temperature (39.8 °C) peaked at a level of concern. Subjects unanimously reported cooling to be inadequate at the higher workloads. Subjects generally reported head cooling to be adequate via air circulation and believed a cooling cap would not significantly improve the overall thermal balance.

As shown in Figure 25, the subjects applied different speed profiles to complete the 10-km distance.

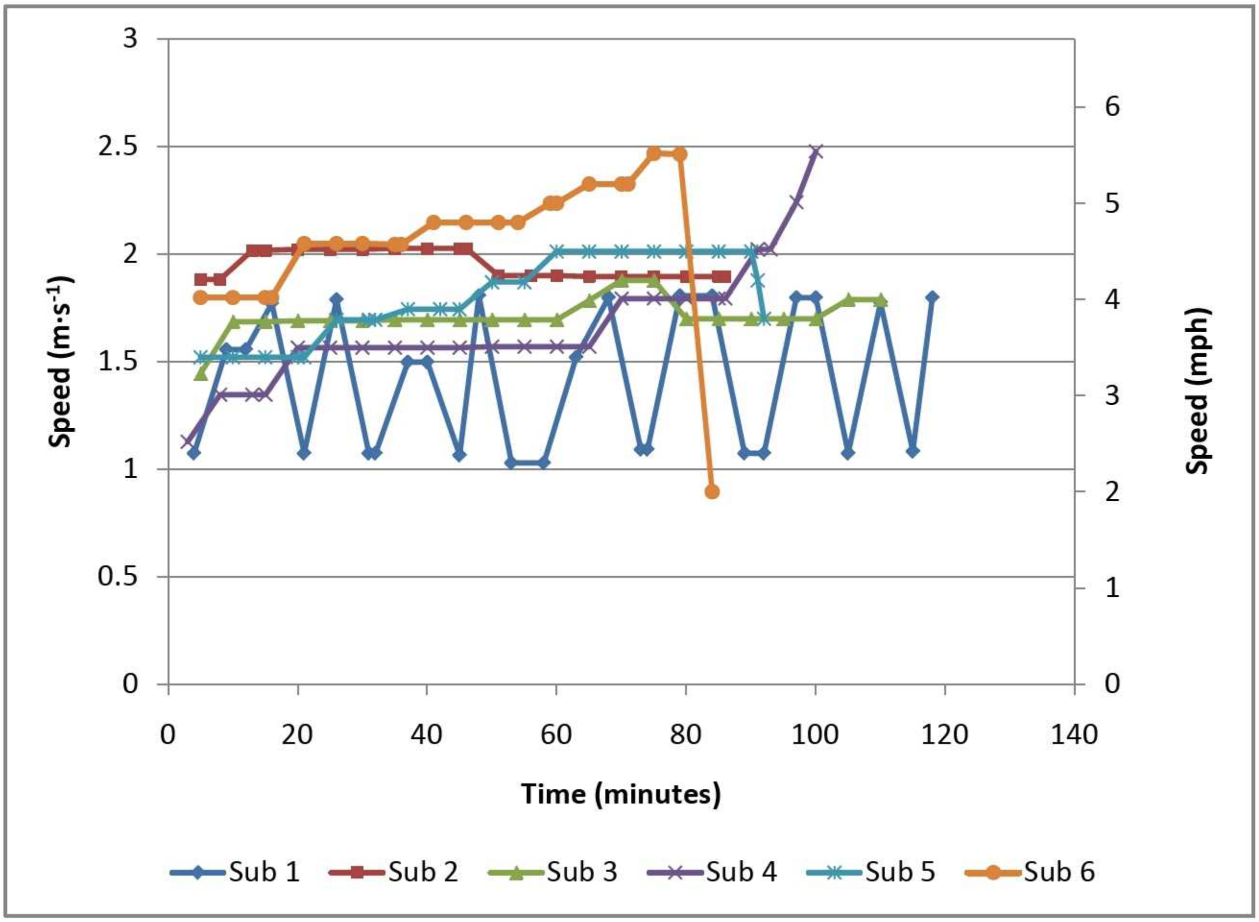



**Figure 25. 10-km walkback speed profiles for all subjects**

All subjects were provided 32 oz of water in an in-suit drink bag affixed with Velcro to the sternum area of the inner suit torso, with a bite valve placed near the crewmember's mouth. This configuration was a special accommodation for this test because of the expected duration of the exercise. As a result, the fit of the drink bag was better for some subjects than others. One subject did not use the drink bag due to difficulty accessing the bite valve and another subject could only drink from the bag when he stopped moving. Aside from these instances, the crewmembers consumed 50% to 100% of the water provided, and 1 crewmember would have preferred to have another 20% available.

The 10-km walkback required an average of 944 kcal, with our subjects ranging from 931 to 1068 kcal. All crewmembers felt that a nutritional item, either food such as a bar or energy gel, or flavored electrolyte drink might improve performance and/or endurance.

For the NASA TLX, 3 of the participants selected physical demand as contributing the most to workload (Table 7). Effort was identified by 2 participants as contributing the most to workload.

**Table 7. Weight of each factor contributing to workload**

| Subject | Mental Demand | Physical Demand | Temporal Demand | Performance | Effort | Frustration |
|---|---|---|---|---|---|---|
| **1** | 2 | 5 | 1 | 4 | 3 | 0 |
| **2** | 2 | 3 | 4 | 1 | 5 | 0 |
| **3** | 4 | 1 | 2 | 1 | 3 | 4 |
| **4** | 2 | 5 | 3 | 0 | 4 | 1 |
| **5** | 2 | 4 | 1 | 3 | 5 | 0 |
| **6** | 0 | 5 | 3 | 2 | 4 | 1 |

The scores of each factor contributing to the workload and the final computed score for the NASA TLX are presented in Table 8 and Table 9, showing widespread variability in all categories. The average workload score was 40.5 ± 11.9%, indicating there was a moderate amount of perceived workload (0% to 30% low workload, 30% to 60% moderate, 60% to 100% high).

**Table 8. Score of each factor contributing to workload**

| Subject | Mental Demand | Physical Demand | Temporal Demand | Performance | Effort | Frustration |
|---|---|---|---|---|---|---|
| **1** | 30 | 89 | 20 | 5 | 80 | 31 |
| **2** | 49 | 30 | 48 | 17 | 42 | 8 |
| **3** | 20 | 30 | 20 | 25 | 29 | 19 |
| **4** | 26 | 30 | 30 | 27 | 41 | 12 |
| **5** | 30 | 80 | 9 | 5 | 78 | 7 |
| **6** | 0 | 59 | 29 | 18 | 58 | 0 |

**Table 9. Computed NASA TLX score**

| Subject | Score |
|---|---|
| **1** | 52.3 |
| **2** | 40.5 |
| **3** | 22.5 |
| **4** | 31.2 |
| **5** | 52.9 |
| **6** | 43.3 |

For the target tracking task, the subjects were aware that this was a test to assess their cognitive capability. With the exception of 2 of the participants, the results were gamed; therefore, the results of this target tracking task were invalid. Of the 2 participants who did not game the system, one's performance was the same pre and post-walkback and one's showed an increase in time to completion.

# Discussion

## *Determination of PTS*

Originally, the plan was to determine subject speeds by use of Froude numbers. Under 1-*g* conditions, research has shown that humans change from a walk to a run at a Froude number of approximately 0.5 (Hreljac, 1995). This trend of moving from a walk to run at 0.5 has been proposed to be consistent independent of gravity level based on the theory of dynamic similarity (Donelan & Kram, 1997). Therefore, the predicted PTS for each subject was computed as the speed corresponding to Fr = 0.5 with $g = 1.63\ m{\bullet}s^{-2}$ (lunar gravity) or $g = 3.68\ m{\bullet}s^{-2}$ (Mars gravity). In both cases of reduced gravity during this test, the actual Froude number at PTS was much higher than 0.5.

Kram, et al (1997) investigated the effect of reduced gravity using an overhead suspension system on walk-run transition speed and found that near lunar gravity, transition speeds were between 0.98 to 1.16 $m \cdot s^{-1}$ (2.2 to 2.6 mph) with corresponding Froude numbers of 0.83 to 1.13. They attributed the difference between the actual and predicted speeds to be caused by the fact that in the suspension system, the legs and arms were not unweighted. They theorized that the 1-*g* swinging of the arms and legs acts to effectively increase the gravitational level experienced by the subject. They implied that in a true lunar gravity environment, the PTS would occur at $Fr = 0.5$, because the limbs would be unloaded. However, data collected in actual lunar gravity during parabolic flight indicate that the walk-run transition speeds were similar to those found on the POGO (Scott-Pandorf, 2007). These findings suggest that the locomotive patterns used during POGO tests accurately replicate those that would be used in an actual lunar gravitational environment.

## *Metabolic and Transport Costs of Locomotion*

The energy-velocity tests were undertaken so that specific human-performance factors of the MKIII suit could be understood across a range of gravity levels and ambulation speeds. Results of unsuited and unsuited weight-matched controls were compared to suited tests in an attempt to distinguish specific impacts of the suit. Unsuited 1-*g* controls provided a reference for normal Earth activities.

The metabolic cost of increased weight is the difference between the unsuited baseline and the unsuited weight-matched trials. The suit metabolic cost unrelated to weight would be the difference between the unsuited weight-matched trial and the suited trial at that particular gravity level. Factors that would be included in this cost would be inertial mass, CG issues, pressure-volume work, kinematic and stability constraints of the suit (Carr, 2007). We have performed additional studies to identify the specific contributions of some of these individual factors (Vos, 2008; Stroud, 2008; Norcross, 2008). These tests examined unsuited subjects with 1) varying offload (weight) but constant mass and 2) varied mass, but constant offload and suited subjects with 1) varied offload (weight) but constant suit pressure and mass and 2) varied suit pressures but constant offload and mass. The goal of these tests was to identify the specific metabolic cost associated with weight, inertial mass, and pressure-volume work. The remaining differences may then be attributable to the kinematic and stability constraints of the suit.

While it was a consistent trend that metabolic rate increased with speed, there was no indication of which speeds may be most efficient when looking at metabolic rate alone. Efficiency of locomotion can be determined by the $O_2$ transport cost and can be thought of as the human's "gas mileage". In lunar-suited conditions, there was a clear trend of decreasing transport cost as speed increased. While a crewmember might expend more energy on a per minute basis by traveling at faster speeds, the metabolic cost per kilometer would actually be less. Despite improved efficiency with increasing velocity (Figure 26), the metabolic work of locomotion generates a continuous rise in heat production as speed increases. The current Shuttle EVA suit's cooling capacity ranges from 2000 BTU/hr for 15 minutes to 1600 BTU/hr for 1 hour to 1000 BTU/hr for up to 7 hours (Extravehicular Mobility Unit Design and Performance Requirements Specification, Specification No. SVHS7800, Hamilton Sundstrand). The Apollo EVA suit cooling capacity was different. The suit used for Apollo 9, 11, 12, and 14 was sized to provide a total cooling capacity of 4752 BTU/hr up to 1584 BTU/hr for 3 hours. The suit used for Apollo 15 through 17 had a cooling capacity of 7128 BTU/hr and an expected use of 990 BTU/hr for 7 hours (Waligora, 1975). While transport cost improved with increasing velocity during suited lunar trials, cooling capacity would be a significant limiting factor both in terms of maximum allowable speed and necessary duration of a 10-km walkback. At speeds above 1.3 $m \cdot s^{-1}$, the heat production would begin to exceed current and past cooling limits, resulting in either increased core body heat storage or in a significant slowing of the crewmember's speed.

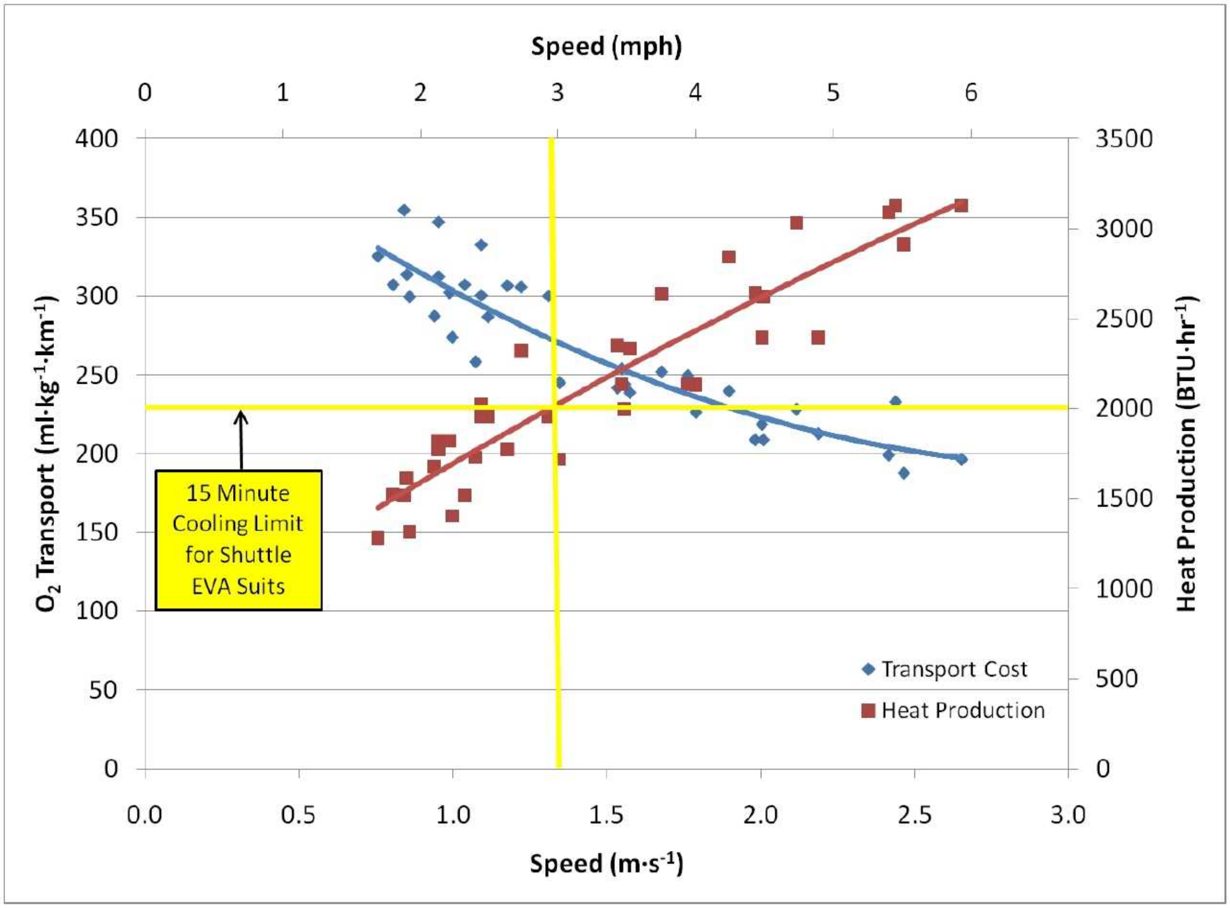



**Figure 26. Suited lunar O2 transport cost and heat production**

Without improvements in cooling for future suits, crewmembers on lunar EVA would not be able to exploit the increased efficiency available at faster ambulation speeds, resulting in increased consumable requirements to cover the same distance.

The improved transport cost of suited locomotion at higher speeds could be due to several factors. One factor is that the overhead POGO components are massive enough to provide stability such that the subject may not need to exert as much forward propulsive force as would actually be required to maintain a given speed on the treadmill. Instead, the stabilized subject is able to jump in the air vertically and have the treadmill belt travel underneath them. Due to the method of force plate instrumentation to the treadmill as described in the data collection techniques, Test Hardware shear force data, which would be required to assess the validity of this theory, could not be collected. Another factor might be a change in gait style such that greater forward distance can be achieved without significantly greater increase in vertical excursion of the COM. Another possible factor might also be an energy storage/return property of the suit that is enhanced by an increase in speed. Carr & Newman (2007) suggested that the pressurization of the suit acts as a spring and stores energy during impact and releases that energy throughout the remainder of the gait cycle. While this may be the case, there is little to suggest that this energy storage would be enhanced by an increase in speed. Future studies will consider all of these factors and look to see what factors significantly enhance transport cost. Understanding these factors will allow EVA suits to be designed for optimal efficiency across a range of working conditions associated with exploration objectives, from discrete geology tasks to contingency traverses.

Moving from Moon to Mars gravity, the metabolic cost of unsuited ambulation were generally similar during walking speeds and slightly higher in Mars gravity for running speeds, suggesting that subjects may expend roughly equivalent energy to maintain stability at 1/6 *g* as they do to carry the additional weight of 3/8 *g*. This trend does not continue for the unsuited weight-matched and suited trials indicating that the metabolic cost of the increased weight exceeds any benefits of increased stability as speed and weight increased.

In lunar gravity, the relationship of weight to increased metabolic cost was directly affected by speed. At the lowest walking speeds, weight added little to the overall metabolic cost of the suit. As speed increased, the cost of weight steadily increased and at the highest speeds, weight made up approximately 50% of the increased metabolic cost of suited locomotion as determined by the difference between the unsuited and unsuited weight-matched conditions. In Mars gravity, weight had the same overall impact, but the percentage of the total metabolic cost of the suit due to weight was significantly smaller. Where it could be calculated, the percentage of metabolic cost due to weight ranged from 8% to 10% and the other factors such as mass, pressure and kinematic constraints accounted for 90% to 92% (Table 5).

Other factors beside weight that contribute to the metabolic cost of the suit include pressure-volume work, inertial mass, CG change, and kinematic and stability constraints. How these factors influence metabolic rate at different suit weights and/or gravity levels is currently being evaluated by our group. From these data, we surmise that an acceptable suit mass for lunar gravity would likely not be acceptable for Martian gravity. There also might be a wider range of acceptable suit masses in lunar gravity than Martian gravity. Further studies must be planned to understand the sensitivity and acceptable range of suit mass for each gravity level to derive an optimal range of metabolic and transport costs per unit of suit weight.

It was clear that the suited metabolic cost of locomotion in Martian gravity was too high to be acceptable with the 120-kg mass MKIII suit in POGO configuration. While the additional weight accounted for a portion of this increased metabolic cost, it was not the major contributor. We believe that the kinematic constraints and rotational inertial mass of the MKIII suit was a major factor in this greatly increased metabolic cost. As seen with the increased number of waist cycles (see Figure 14), as ambulation speeds increased on Mars, the subject must rotate around the waist joint with greater frequency to assist in moving the legs from one position of support to the next to maintain the given velocity. The frequent starting and stopping of the inertial mass along this low friction waist joint made ambulation at 3/8 *g* and greatly increased the metabolic cost.

## *Biomechanics of Locomotion*

The GRF data provides a useful tool for researchers and suit designers. For bone and muscle countermeasures development, GRF analysis may be used to help quantify the amount of loading provided to the musculoskeletal system during EVA locomotion. Such data will be important for understanding what countermeasures are necessary for preservation of bone and muscle mass, and the degree to which EVA provides musculoskeletal loading. This will enable the optimization of exercise equipment to complement the loading provided by EVA. Additionally this GRF data will be critical to developing an appropriate EVA simulation for conducting lunar EVA prebreathe protocol verification trials. Previous studies (Conkin & Powell; Vann) have suggested that decompression sickness (DCS) risk increases during ambulation in 1 *g* compared to microgravity EVAs, which involve very little lower body musculoskeletal stresses. EWT results suggest that suited lunar GRFs at running speeds can approach 1-*g* (unsuited) walking levels and, therefore, should be considered in lunar EVA prebreathe protocols to ensure acceptable risk levels for the lunar environment.

To quantify the stability of the suited locomotion, the angular positions and velocities of the ankle, knee, and hip are used to define state vectors for a given series of strides. These state vectors of the cyclic motions can be transformed into a linear series of equations, using Floquet's theorem. The end results of these transformations are eigenvalues termed Floquet multipliers. Although originally used in robotic locomotion analysis, this analysis is now being used for human locomotion (Cheng & Lin, 1995). The maximum Floquet multiplier across a range of strides is used as a measure of stability and the closer the maximum Floquet multiplier is to 1, the less stable the gait and longer it takes the individual to return to steady state locomotion. EWT results clearly showed that suited locomotion resulted in higher Floquet multipliers than unsuited conditions, but in general the values were below 1.

### *Subjective Factors of Locomotion*

Since humans will be the ultimate users and beneficiaries of any EVA suit improvements, it is critical to understand impacts to performance and comfort on a subjective level.

In both lunar and Mars conditions, suited GCPS ratings were higher than both unsuited conditions. This was expected as the crewmember must learn how to work with and within the MKIII EVA suit. Because most subjects were new to the use of MKIII suit on the POGO for locomotion, we expect that there is a period of learning/programming before a comfortable level of use is reached within the suit. As the energy velocity studies were the first portion of the test, it is likely that the GCPS and possibly the RPE values may be higher than what would be seen in later studies with the same subjects. With lunar-suited conditions, the GCPS increased as speed increased indicating that improvement was warranted if it is projected that the suits may be used at those higher speeds, although many points were still in the acceptable range. Mars-suited conditions had the highest GCPS by far and were never in the acceptable range. In combination with the metabolic data, this indicates that the MKIII suit or a design with similar characteristics would not be acceptable for Mars under similar conditions as presented in this test.

In lunar conditions, there was little difference between unsuited GCPS ratings, but in Mars gravity, the unsuited weight-matched conditions were consistently lower than standard unsuited conditions. Weight alone likely accounts for most of this difference. When offloading the subject to the Mars weight-matched condition, their ground weight was quite similar to what it normally would be in 1 *g*. A rating of 2 on the GCPS refers to one's unsuited performance of the task in 1 *g*. Because of this similarity, most subjects tended to rate the Mars weight-matched condition a 2. Even with these considerations, all unsuited conditions, with the exception of a few test points within the Mars-unsuited condition were typically considered acceptable (GCPS $\leq 3$), but there still were many instances of a GCPS rating indicating that improvement was warranted (GCPS of 4-6).

Another consideration resulting in elevated GCPS ratings could have been an artifact of the inability of the harness and gimbal system to provide a consistent CG across subjects. The harness (unsuited) and gimbal (suited) mechanisms used to provide the partial-gravity simulation induced changes to the overall CG of the subject/suit/support equipment system that were difficult to both standardize and quantify. Although subjects were able to freely choose their spider and stinger settings on the gimbal, all subjects chose to align the total system CG just forward and low of the gimbal axes of rotation. Future tests need to examine how a change in the alignment of system CG and gimbal axes would affect human performance. The team will be developing improved harnesses for unsuited studies and a gimbal mechanism for suited trials that allow more precise and consistent placement of the CG. These improvements will be needed to allow systematic investigation of the effects of CG on metabolic and biomechanical parameters during representative EVA tasks. Future studies may allow determination of whether GCPS ratings will remain similar to those reported during this test or if increased familiarization with unsuited ambulation on the POGO, a better harness and more control of CG will decrease the average GCPS rating.

RPE trends were very similar to measured metabolic rates indicating that for evaluations where measurement of metabolic rate is not possible, RPE could be an acceptable substitute when making rank order or more general comparisons. Actual conversion of an RPE to a metabolic rate would be too limited given the small subject set and multiple different test configurations. A more accurate approach to predicting metabolic rate would be to use a subset of subjective, subject, and system factors. Preliminary mixed modeling analysis indicated that a combination of the RPE, a suited/unsuited factor and the GCPS rating were all statistically significant predictors for metabolic rate.

### *10-km Walkback Test*

The first and unexpected finding of the 10-km portion of the test was that crewmembers could indeed ambulate 10 km in the MKIII suit at simulated lunar gravity, and did so rather easily. Even after completion of the energy-velocity test sessions, many involved in the test expected that crewmembers could complete perhaps half of the distance. It was believed that suit fit issues, and boot discomfort in particular, would limit the ability of crewmembers to withstand that much time or number of gait cycles in the suit. It was furthermore expected that crew-members would need in excess of 3 hours to complete the task, however, the mean time to complete the 10 km was only 96 minutes.

It should be noted that this test was performed on a level treadmill. Lunar-like conditions including terrain, topography, and navigation could significantly alter the results likely increasing time and/or metabolic rate needed to complete a 10-km walkback. Results from 1-*g* studies in lunar-like terrain near the Haughton Mars Project indicated that the actual distance needed to travel 10 km increase on average by 7% due to factors such as navigation and route selection. Also compared to speed and grade matched treadmill trials, the lunar-like terrain trials had a metabolic rate that was an average of 56% higher (Norcross, 2008).

Metabolic data also indicated the relative ease with which subjects completed the walkback. An average work rate of 51% $VO_2$pk, with a range of 45% to 61%, would generally be classified as low to low-moderate exercise intensity and was consistent with the average RPE of almost 12.

GCPS was on average higher than desired at an average of 3.5. If improvements were made to the EVA suit resulting in lower GCPS ratings, we would expect that the metabolic rate at any given speed would be lower, therefore increasing transport cost or efficiency.

To complete the walkback, subjects generally started the test conservatively at speeds less than 4 mph and progressively increased their speed to a level at which stability and comfort levels were satisfactory. One subject used an interval-type strategy and in the post-test debrief reported it was successful for him because alternating between walking and running alleviated the hip discomfort from walking and the heat production and foot discomfort from running. The majority of the subjects, however, experimented to find the fastest velocity tolerable without thermal discomfort. Future tests will be designed to better understand the complex interrelationships of physiologic and engineering variables, which allow some subjects to tolerate higher suited velocities with lower heat production. After the test, some subjects reported they would likely ambulate more slowly to save consumables in an actual nonemergency lunar scenario. Based on the metabolic results, this action might decrease the rate of consumables used on a per hour basis, but would actually cost the crewmember more in total consumables used because it would take more time to reach the final destination. Going slower also may not allow the crewmembers to take advantage of any mechanical benefits of locomotion that the suit may be providing to decrease transport cost with increased speed. A greater issue that explaining to the crew that going faster will actually save consumables is that the cooling capacity of the suit may not allow the crewmember to take full advantage of the better transport cost at higher speeds. If the 10-km walkback is to be a true contingency, then the cooling system would need to be sized so that the improved transport cost at higher speeds can be realized.

Since most subjects completed the 10-km walkback without difficulty and there were no consistent results from the NASA TLX or the target tracking test, there were no results to indicate decreased cognitive or physical performance post 10-km walkback. Given evidence that the crewmembers gamed the target tracking system, the test team will be careful to blind the subjects as much as possible to the test conditions and purpose of certain evaluations in the future.

Based on the energy expenditure rates found in this study, caloric supplements may be desirable for lunar missions dependent upon the planned EVA operations. Under the assumptions of this test, crewmembers would have been on EVA for 4 hours, driving the rover to the work site and performing the nominal tasks of the day, prior to a rover failure. Based upon Apollo surface EVA data, this would equate to the consumption of approximately 1000 kilocalories (kcal) before beginning the excursion back to the habitat (Waligora & Horrigan, 1977). The 10-km walkback required an average of 944 kcal, with our subjects ranging from 931 to 1068 kcal. Thus the total energy needs for a sample EVA with this walkback-type contingency would approach 2000 kcal, which is approximately two thirds of the recommended daily energy intake (3000 kcal/day) for a 70 kg male on NASA exploration missions (NASA-JSC, 2005), demonstrating need for caloric supplements beyond the additional 50 kcal on EVA days currently advised.

### *Study Limitations*

This study was undertaken as a pilot experiment because of the complexity of integrating personnel and facilities from various JSC organizations and because the testing protocols were the first of their kind (i.e., different than methods employed during the Apollo era). As a result, caution must be used when interpreting and generalizing the findings of this study. Most notably, trials in this study were performed on a smooth, firm treadmill surface while a portion of the subject's weight was lifted by a servo-controlled device that limited movement degrees of freedom. Development of simulators that permit more realistic ambulation on planetary surfaces is required.

This initial look at suited ambulation used 6 male subjects and the MKIII suit. How representative these subjects are of the total astronaut population is unknown. As these studies progress and eventually when new prototype suits are tested, every effort should be made to include as many subjects as possible as well as to characterize the subject pool's fitness and anthropometry so that an understanding of what factors contribute to improved performance can be understood.

The key other areas involving study limitations and lessons learned included hardware, test set up, and study design. As mentioned previously, the Challenger treadmill was used for this test despite known shortcomings. The team suspected the treadmill belt (27 in.) was not wide enough for subjects to ambulate in 1/6-*g* suited conditions without stepping off the belt, but tests conducted during the POGO characterization determined this treadmill acceptable for EWT use. During EWT trials, subjects only occasionally stepped off the belt with either a toe or heel, but this did not significantly impact their gait. However, several subjects did report that they consciously modified their gait with the belt width in mind. The team has since purchased a new treadmill with a walking surface that is 5-ft wide and 8-ft long to ensure that true gait biomechanics are not compromised.

A significant limitation of the suited gimbal system was the inability to precisely control or accurately set the total system CG in relation to the gimbal center of rotation. Standard procedures were used to configure the systems such that the subject was suspended in a neutral posture while in the suit and then subjects adjusted to their preferred position. All subjects freely chose a slightly forward and low position of the system CG. Improved designs of the gimbal system will be required to allow precise and consistent application of CG alignment and to allow systematic variation of CG locations to study the effects of CG on human performance.

Several issues with study design, such as the insufficient thermal data during suited trials, will be addressed in future investigations. There is also the possibility of learning effects associated with ambulation (both suited and unsuited) using the POGO system. Familiarization sessions will be incorporated into future studies and if it is determined that there are significant learning effects, future tests will be designed to incorporate systematic familiarization sessions.

The test team is limited in the interpretation of thermal data from this test because skin and core temperature measurements transmitted data inconsistently to the wireless monitor placed outside the suit. This is likely correctable by changing the monitor's data collection mode setting, however, the team will conduct further verification of these thermal measurement devices. Future tests will include accurate measurement of heat removal to determine the entire thermal balance picture, including at a minimum sweat weight loss, LCVG flow rate, and inlet/outlet temperatures. The team also learned that determining regular subjective ratings of thermal comfort would have been valuable to supplement core and skin temperature measurements, but this was inconsistently applied during the 10-km tests.

## *Lessons Learned*

Initially during ambulation, subject speeds were to be based on the Froude number. However, under the reduced gravity conditions, using the Froude number did not allow a great enough variety of speeds and was thus abandoned and subject speeds were selected on the basis of each individual's PTS. Initially this was done so that walking and running could be compared across different gravities independent on speed. Given that distinctions between walking and running seem to be less clear in reduced gravity, it may be of benefit to switch to fixed speeds for future tests. Also having individual speeds did not allow for direct comparison between conditions and subjects.

Overall, of the 252 possible trials in the EWT, 169 were used for biomechanics analysis. Some conditions such as the suited condition in Mars gravity proved too difficult to complete, but there were other nonexertional related reasons. Because of safety concerns, primarily high discomfort in the unsuited harness, some of the unsuited testing was halted. This led to the final 2 subjects being retested, but with a different harness setup. Because of this crucial difference from the other subjects, those 2 subjects could not be included in the earlier grouping for biomechanical comparisons, although they were included for metabolic comparisons. It was also common for subjects to have inconsistent gait patterns and experiment with their gait during data collection. For biomechanical variables, this made it nearly impossible to average across a trial when the gait changed across strides. For metabolic and subjective data, we assumed that changes in gait across a trial would not be significant enough to affect these variables, especially because humans tend to gravitate toward the most energy efficient movement solution possible. In future tests, the subjects will be instructed to maintain a constant gait throughout biomechanical data collection and may possibly be instructed to employ a symmetric Earth-like gait throughout the study even if an asymmetric gait is favored. Future studies also could examine how changing gait affects results. Finally, the unsuited harness comfort needs to be improved without encumbering on the ability of the subject to move freely.

The limited number of gait cycles also made data analysis difficult. There were only 20-gait cycles for unsuited subjects and 10-gait cycles for suited subjects collected. With so few gait cycles there is also an increased effect of any anomalies in the gait cycle. In attempt to remedy this obstacle, while still considering time constraints and the need for an aggressive schedule in future testing, a compromise of 30-gait cycles was reached for both suited and unsuited future tests.

Force data and motion data had to be collected using 2 separate systems. The Vicon iQ software was made for motion capture and built for the animation industry, which has no need for analog input or triggering. It also did not allow for real-time viewing of the data. Synchronization between the motion capture from the Vicon iQ software and the force data system was achieved via a near-infrared light emitting diode triggered by the start of force capture. It took an extensive amount of time to re-import the force data into the motion trials and a custom Vicon file format had to be written in order to re-import the force data.

For future tests, the Vicon Nexus software (released late 2006) should be used to collect data. This software has a life sciences design that allows for triggering and analog input. Real-time viewing of motion and force data is also a benefit to the Vicon Nexus software. The software also has improved calibration capabilities.

A minimal marker set was used based on PluginGait. Because of the minimal marker set, the sacrum marker often had gaps that could not accurately be filled in using the available software. Similarly, the back markers often had gaps due to obstruction from the gimbal. For future tests there will be an expanded marker set based on PluginGait. Two posterior suprailiac markers will be used instead of a single sacrum marker. Redundant markers will also be used on the PLSS corners along with rigid body fill to create back markers.

There were several limitations of the Vicon 612/Small Volume (SV) System hardware used. Because the hardware is designed for small volume, the capture volume used for the walkback was at the upper limit of allowable capture volume. The system worked on a binary reflection principle, meaning that a reflection was synonymous with a marker. The reflective nature of the suit therefore caused many extraneous reflections that were interpreted as markers. The low resolution (< 1 megapixel (MP)) coupled with the large capture volume, lowered the accuracy of the system. In an attempt to address these issues, a Vicon MX+ system was purchased for future tests. This system has a 4.0 MP resolution and large volume capability. The Vicon MX+ system uses grayscale reflection processing that means that the markers are identified on-board cameras themselves and the centroid locations are sent to the software for further processing. This lowers the 'false positive' markers from extraneous reflections.

The in-suit metabolic system currently relies upon $CO_2$ analysis combined with a known subject by subject relationship between $VO_2$ and$VCO_2$ per each subject's $VO_2$peak test. Inclusion of an $O_2$ analyzer to allow for actual $VO_2$ calculations would improve the overall accuracy of the metabolic system. In addition, adding an outlet flow sensor would allow any suit leaks to be quantified.

As the initial study in this series, it was uncertain whether a larger treadmill was required or just preferred. Feedback from most subjects was that a larger treadmill would be preferred. Figure 27 shows representative step width data , which shows an increase in step width with decreased gravity and also showed times where the subject's foot came in contact with the edge of the treadmill belt rather than right on it.

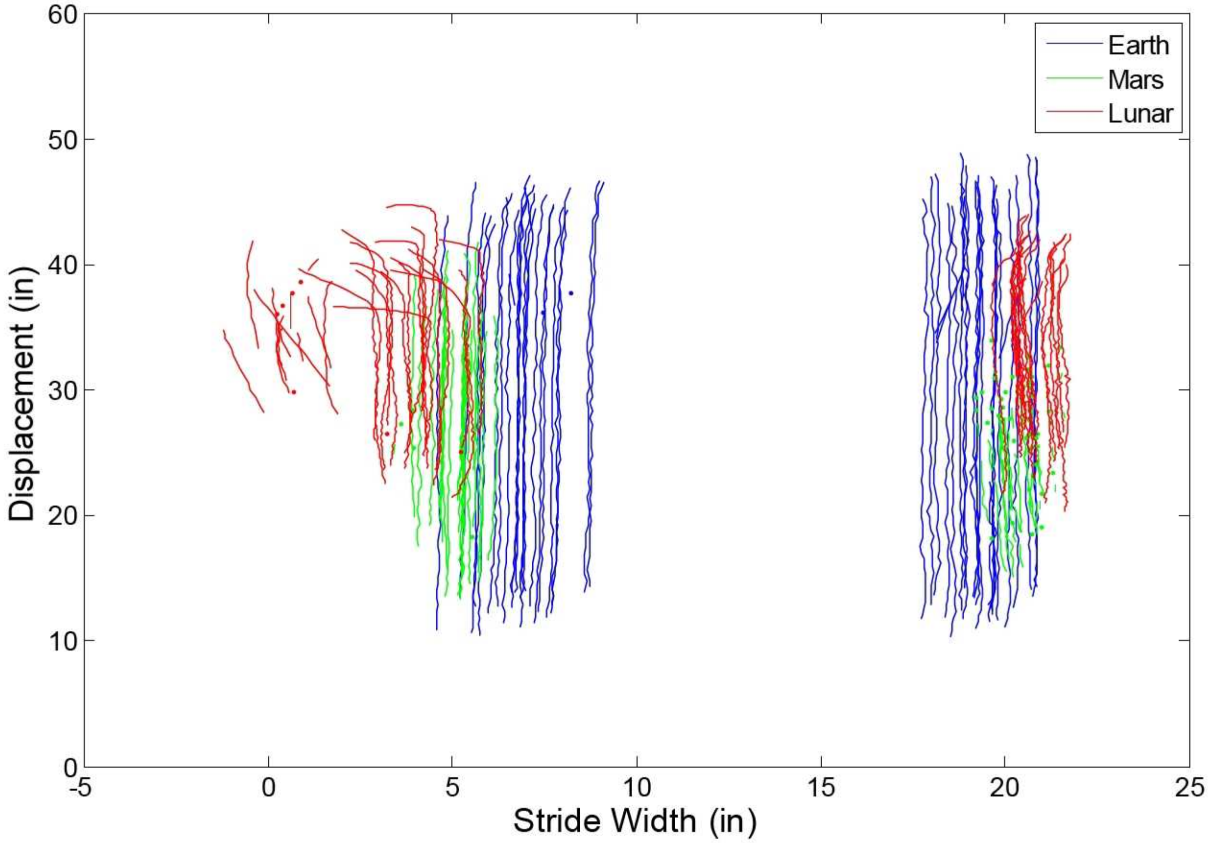



**Figure 27. Representative step width data for one subject at Earth, Mars and lunar gravity at a running speed**

# Conclusions

The primary objective of this study was to collect human performance data and produce a crew consensus regarding the feasibility of performing a suited 10-km walkback. All subjects completed the 10-km walkback in less than 2 hours and completed the test with little difficulty working at about 50% $VO_2$pk.

A secondary objective of the study was to understand the specific human performance limitations of the suit compared to matched unsuited controls. Preliminary analysis indicated that the metabolic cost of the suit was significant compared to unsuited controls. Weight-matched unsuited trials provided an initial estimate accounting for the metabolic cost of the suit due to weight, but additional factors such as inertial mass, CG alterations, pressure-volume work, and suit kinematic constraints could not be isolated. Additional tests will be performed to evaluate these other suit related factors.

Another secondary objective was to collect metabolic and GRF data to allow development of an EVA simulator to be used on future prebreathe protocol verification tests. This study provided an initial characterization of suited ambulation but future tests will be needed to understand other EVA related tasks.

Proving human performance and suit biomechanical data for use in suit and portable life support system (PLSS) design was another secondary objective. Baseline ambulation metabolic rates will allow for understanding of PLSS needs depending on the amount of ambulation expected in the lunar operational concepts. $O_2$ transport cost values indicated that optimum efficiency is achieved at faster speeds for lunar suited ambulation, but current cooling capabilities of the Shuttle EVA suit and Apollo suits would be insufficient to take advantage of this improved efficiency. Results of this test also clearly indicated that crewmembers may perform well on the Moon but may not perform well on Mars. In the lunar trials, the suited metabolic rates were all submaximal, whereas in the Mars-suited trials, subject rapidly approached near maximal efforts while brisk walking.

A final secondary objective was to assess the cardiovascular and resistance exercise associated with partial-gravity EVA to be used in planning appropriate exploration exercise countermeasures. While the metabolic rate for lunar-suited and unsuited ambulation was characterized, there exists little data to quantify the resistive exercise dose from suited ambulation. In addition, many other tasks need to be characterized and a clear operational concept defined before exercise countermeasures can be appropriately designed.

Additional considerations from this test include the development and refinement of data analysis methods that will form a set of 'standard measures' for future studies that look at effects of suit weight, mass, pressure, CG, and kinematic constraints for both ambulation and exploration tasks. Tools resulting from the EWT include analysis software to rapidly post-process motion data to determine the number of cycles on any joint of the suit as a function of time and velocity, and to provide a quantitative index of stability. These analysis tools will be effective for developing suit cycle requirements and will provide significant cost savings during suit certification compared the conventional methods of manual video tape review.

In summary, the EWT not only answered the primary objective of the study, but provided an entry into the systematic assessment of the complex interrelationships of the human-suit system in a partial-gravity environment. All of the data, analysis tools and lessons learned from this study will be used to refine NASA's understanding of the various parameters pertinent to performing suited exploration EVA tasks. Ultimately, these studies will provide information to the EVA community for making evidence-based recommendations to optimize suit design for the targeted operational environment, operational concepts, and crew anthropometric range.

# Appendix A: Submaximal Test Termination Criteria

Test Termination Criteria for All Submaximal Testing

1. Subject request to stop at any time
2. Subject's heart rate or measured $VO_2$ at level > 85% $VO_2$pk for 2 minutes or more
3. Failure of PGCS/POGO hardware and/or treadmill system

ADDITIONAL Test Termination Criteria for Suited Submaximal and 10-km Testing

1. Expired $CO_2$ levels greater than 5%
2. If subject reports discomfort rating $\geq$ 7 (on 10-point scale) for 2 consecutive recording periods, subject will be asked to terminate the test. If subject asks to continue, they will be allowed to continue until they meet condition 3
3. Discomfort rating $\geq$ 7 for 3 recording periods (may be nonconsecutive) or severe pressure point
4. Engineering hardware failure such as in suit or suit environmental control. (These standard/approved engineering termination criteria were described in the detailed test plan (CTSD_AHI_0009) and addressed in the test readiness review (TRR).

# Appendix B: 10-km Ground Rules

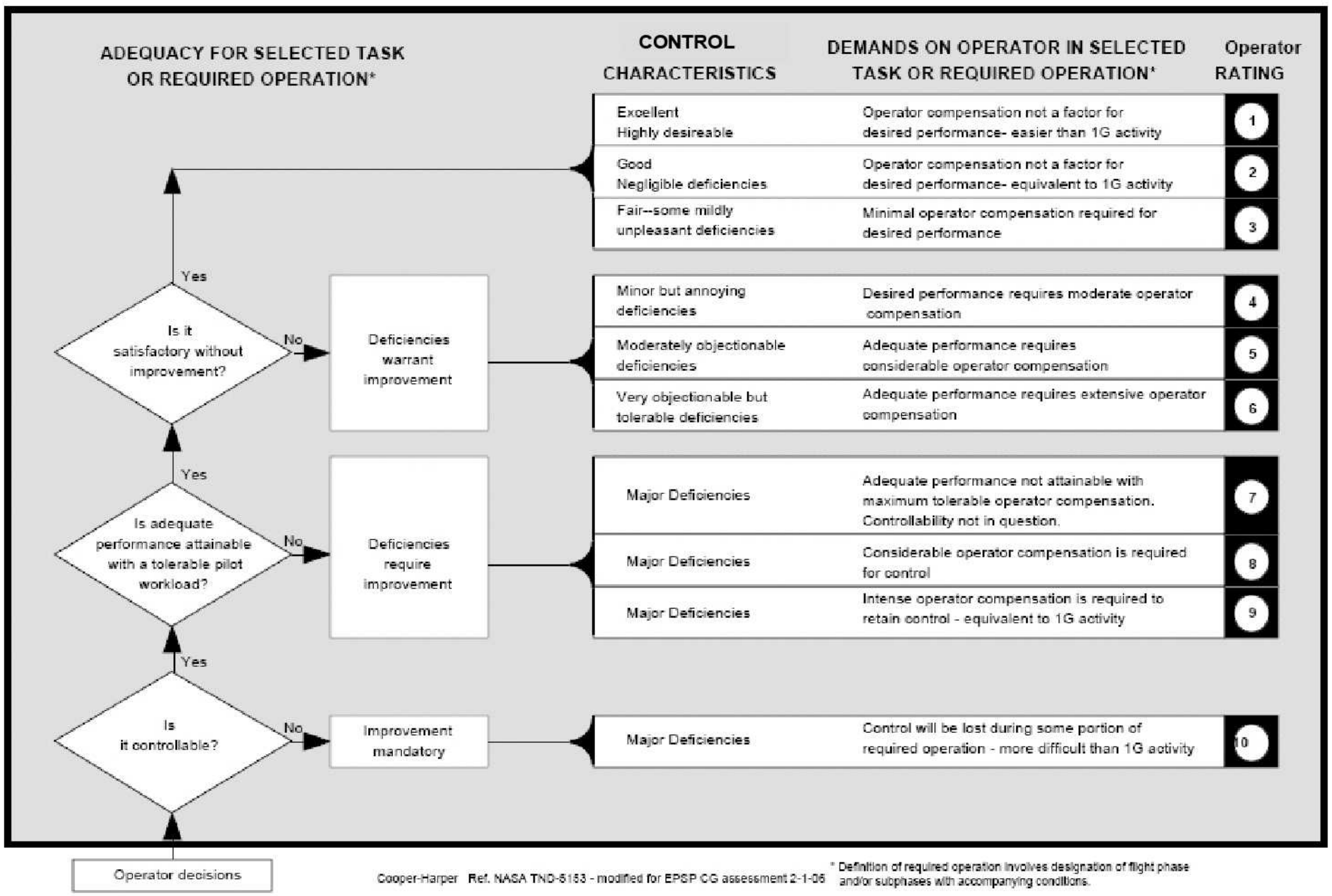
Ground Rules for the 10-km Walkback Session

1. Operation of all engineering systems and equipment to record metabolic rate (met rate), GRF vectors, and motion analysis must be nominal to start each test. Skin and core temperatures and LCVG delta temperature, heart rate (HR), and electrocardiogram (ECG) are desired, but not required for test start.
2. Up to 60 minutes into the test (excluding trouble shooting time), the operating procedure is to stop the test and trouble shoot any required issue for up to 20 minutes. If the problem cannot be fixed, then proceed to terminate the test.
3. At any time beyond 60 minutes into the test (excluding trouble shooting time), the operating procedure is to stop the test and trouble shoot up to an additional 20 minutes (total of 40 minutes for the entire test) for loss of critical engineering systems or met rate, GRF, or motion analysis. If met rate, GRF or motion analysis is not fixable in that timeframe, then continue the test until 10 km is achieved or other test termination criteria have been met.
4. Multiple critical systems are involved in this test, and failure of any of these may result in termination of the test within the guidelines set forth in the previous paragraph. A test termination condition may be initiated by the test director, test subject, medical officer, test safety officer, suit technician, treadmill technician, facility representative, or test team member. This is done to ensure the safety of the test subject and investigators, minimize damage to hardware and facilities in use, and assure the quality of the scientific data collected. Specific criteria for these systems are outlined in the detailed test plan.

# Appendix C: Ratings Scales for Subjective Measures

## *Gravity Compensation and Performance Scale*

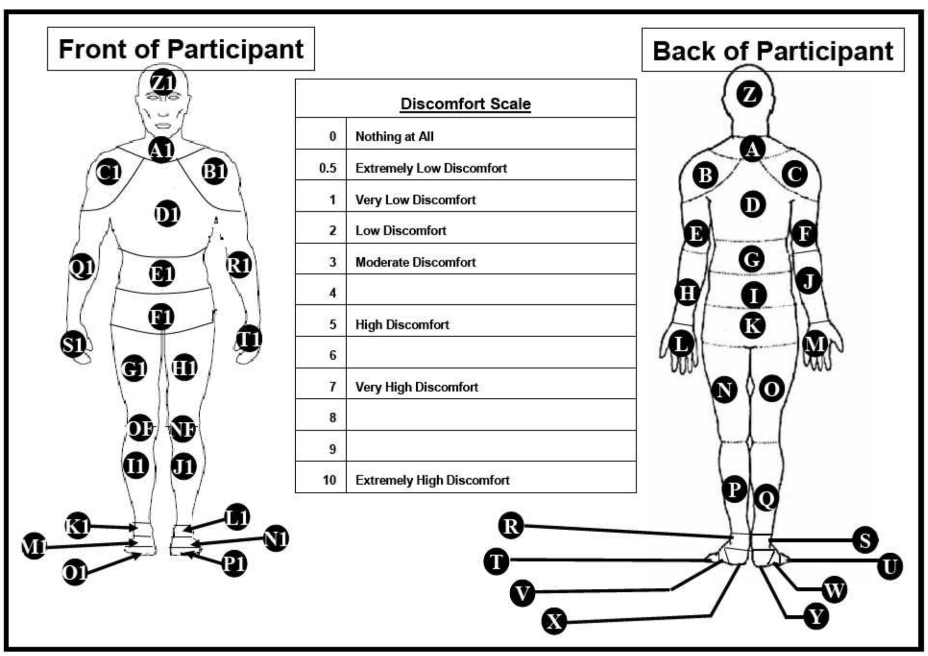
HANDLING QUALITIES RATING SCALE



## *Borg Rating of Perceived Exertion Scale (RPE)*

| | |
|---|---|
| 6 | No exertion at all |
| 7 | Extremely light |
| 8 | |
| 9 | Very light |
| 10 | |
| 11 | Light |
| 12 | |
| 13 | Somewhat hard |
| 14 | |
| 15 | Hard (heavy) |
| 16 | |
| 17 | Very hard |
| 18 | |
| 19 | Extremely hard |
| 20 | Maximal exertion |

## *Corlett & Bishop Discomfort Scale*



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